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Agricultural Experiment Stations

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RATES OF RUNOFF FOR THE DESIGN OF CONSERVATION STRUCTURES IN THE HIGH PLAINS OF COLORADO AND NEW MEXICO

By

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FOREWORD

This publication is one of a series containing information for the hydrologic design of spillways, diversions, culverts, terrace outlets, and other structures where peak rates of runoff govern design. In it an attempt has been made to utilize the results of Soil Conservation Service research and all other available pertinent information to the end that data in usable form be available for use in soil and water conservation and other activities requiring information on maximum rates of runoff.

In making this information available, attention must be called to its limitations. It is applicable to certain soil and cover conditions which occur frequently in the High Plains of Colorado and New Mexico (fig. 1). This information must not be used for other soil conditions in this region because of important differences in runoff characteristics. The basic data from which the values given were derived cover a comparatively short period of record, varying from 6 to 9 years. This period may not be entirely representative, since it includes portions of the drought period of the "thirties" and also of the moderately humid succession of years in the early "forties." Published information on the high rates of precipitation which are necessary for the production of peak rates of runoff is limited in scope and the locations of the longer records are widely separated. With these limitations, revision in recommended values will be necessary as more extensive records and improved methods of analysis become available. Until that time, it was felt that the need for data on peak rates justified the immediate release of whatever information was now available.

In an endeavor to present the results thus far obtained in a form which will be of maximum utility, technicians charged with responsibility for general standards governing design and farm planners and field men engaged in actually putting the work on the land have been freely consulted. These technicians have designated the types of structure being planned for which data on peak rates of runoff are required and the range in the sizes of the watersheds contributing runoff to these different types. These discussions developed that in many locations the design and lay-out of all but major structures is in the hands of farm planners or others without formal training in structural or hydraulic design, and that it would be desirable that a portion of the data be in a form that may be readily used by them. In other locations, most of the design and lay-out work is performed or closely supervised by men with engineering training. In all instances, the more important structures are designed and supervised by experienced engineers. For this reason, it has seemed desirable to divide this publication into three portions. Part I includes an introduction, an outline of the experimental set-up and descriptions of the instrumentation, and the procedures used. Part II includes data in

tabular form suitable for use in the design of the great majority of structures by the planners customarily engaged in this work. It also includes additional data for use in the design of the more important structures which is presented in forms readily interpreted by experienced engineers. These data have been compiled in forms which, in many instances, may be incorporated bodily in handbooks or instructions which are issued to the field. No attempt has been made here to convert hydrologic information into structural or hydrologic design; however, where standardization is desirable, it may be found advisable to use this information in determining specifications for sizes and types of structure. Part III includes a discussion of the more important factors which influence runoff.

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Chief of Research

ACKNOWLEDGMENTS

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RATES OF RUNOFF FOR THE DESIGN OF CONSERVATION STRUCTURES IN THE HIGH PLAINS OF COLORADO AND NEW MEXICO

By Hayden K. Rouse, Agricultural Engineer, Division of Drainage and Water Control, Research, Soil Conservation Service

PART I

Introduction

The need for information on runoff from comparatively small areas of agricultural and grassed lands has long been recognized. Although the problem has been faced by the builders of highways for centuries and by railroads and others for many years, little or nothing had been done to obtain factual information over an extended period. The Division of Surface Water, Water Resources Branch of the United States Geological Survey, has conducted systematic work in collecting records of stream flow throughout the country for nearly 60 years. Their work has been limited, for the most part, to the measurement of the flow of perennial streams. In the High Plains of Colorado and New Mexico, there are very few streams of this type originating in the plain's country, and drainageways having watersheds of a thousand square miles often have no sustained flow. As a result, the records of stream flow originating in the High Plains are limited to watersheds having drainage areas of 500 square miles or more.[1]

In addition to these stream-flow records, some studies of the rates of runoff have been made by the erosion experiment stations and State experiment stations on plots of a fractional part of an acre and on small natural watersheds an acre or two in extent.

Between these extremes in areas no records were available when, in 1933, the work of the Soil Conservation Service (then the Soil Erosion Service) began. This involved literally thousands of hydraulic structures on watersheds varying from a few acres up to 5,000 acres, and in a few cases, even larger. At this time, almost the only hydrologic information available to those charged with responsibility for the design of these structures was a processed "Brief Instructions on Methods of Gully Control" by C. E. Ramser. This included curves and tables largely derived from Ramser's observations at the Murchison Farm in Tennessee which covered a period of approximately 1 year, and from limited records then available from the several erosion experiment stations. These curves and tables were accompanied by factors with which an attempt was made to modify the information for general use throughout the country.

The engineers of the Service soon found that further modification was desirable and that the use of arbitrary factors frequently resulted in overdesign with resultant excessive costs or underdesign accompanied by the loss of structures. The field engineers requested information more nearly suited to their locations. This resulted, on August 19, 1936, in a proposal by the Chief of Engineering Division of the Soil Conservation Service that investigations of rates and amounts of runoff from small areas be

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[1]/The records indicate several small watersheds studied by the U. S. Geological Survey in Eastern Colorado and New Mexico. These are snow-fed streams at elevations much higher than the High Plains area.

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FIGURE 1.— GENERAL AREA OF APPLICATION

Note:
Design values recommended in this
report should not be used where
soil and vegetal cover differ materi-
ally from those described in tobu-
lotions and figures.

undertaken under the supervision of the Office of Research. Based upon this proposal, plans of procedure were prepared and sites selected. Beginning in 1937, some 100 small watersheds on 20 demonstration projects and at agricultural experiment stations were established. Those on demonstration projects at Colorado Springs, Colo., and Vega, Tex., are typical. The locations were selected as being representative of the more important agricultural areas of the United States. These studies supplement the more elaborate and extensive investigations being conducted at the three groups of experimental watersheds at Coshocton, Ohio; Waco, Tex.; and Hastings, Nebr.; including many different types of soil, cover, and topography. At the same time, observations on plots and natural watersheds of a few acres were continued at some of the old erosion experiment stations. The data from the Fort Hays Conservation Experiment Station at Hays, Kans., are, in part, representative of the High Plains areas of Colorado and have been consulted in compiling the data presented herein; however, the greatest reliance has been placed on records obtained at the runoff studies projects at Colorado Springs, Colo., and at Vega, Tex.

<center>Experimental Set-up</center>

The runoff studies conducted at Colorado Springs, Colo., and Vega, Tex., were laid out under the broad plan which included installations all over the country. These projects have been conducted to obtain rates and amounts of precipitation, rates and amounts of runoff, records of temperature and relative humidity, and other pertinent information. The Colorado Springs project includes four watersheds while that at Vega, Tex., includes three watersheds. Careful surveys were conducted to record the topography, soils, and vegetal cover of the watersheds. The size and other important physiographic characteristics are incorporated in table 1, page 4.

Detailed soil surveys were undertaken determining the depth to impeding material, texture, etc. The generalized characteristics of the watersheds, using the designations adopted for soil conservation surveys in the Southwest Region, are summarized in table 2, page 5.

Surveys of vegetal cover were made at the inception of the runoff studies program. The areas with native-pasture cover have been classified broadly into general groups which include approximately 90 percent of the area. In general, the remaining 10 percent of the area is in swales or drainageways and supports a denser stand of vegetation then the slopes. The cover conditions as revealed by the original surveys are summarized in table 3, page 6.

For more detailed information regarding topography and soils, see figures 8, 9, 10, 11, 12, and 13, pages 46 to 51.

Plates 1, 2, 3, and 4, pages 7 to 10, illustrate the general appearance and topography of the watersheds.

Beginning in May 1940, intensive studies of infiltration phenomena were initiated on Watershed W-III at Colorado Springs, Colo. This work was conducted by Aubrey L. Sharp and Harold E. Line under the direction of G. W. Musgrave of the Division of Soil and Water Conservation Experiment Stations and included infiltrometer investigations on

TABLE 1.--*Physiographic characteristics*

Loca-tion	Water-shed	Size	Range in elevation		Pre-vail-ing Slope	Range in slope		Slope of principal waterway	Drainage density	Form factor
			From	To		From	To			
		Acres.	ft.	ft.	%	%.	%.	%	ft./acre	
Colo-rado Spgs	W-I	10.6	6699	6749	5	2	6	3.1	113	0.28
	W-II	39.7	6699	6807	7	1	10	3.0	33	.29
Colo.	W-III	35.4	6699	6809	6	3	8	3.1	43	.26
	W-IV	35.6	7099	7195	8&12	4	18	3.2	118	.30
Vega,	W-I	129	3924	4004	1&6	.3	18	3.4	27.8	.57
Texas	W-II	95.9	3906	3978	2&5	2	8	1.6	28.2	.41
	W-III	21.2	3700	3795	10&30	2	80	5.1	303	.39

Note: Elevations are expressed in approximate feet above mean sea level. Prevailing slope is approximate slope applicable to at least 30% of the area. Where two slopes are given, each is applicable to at least 30% of the area.

Form factor is a dimensionless figure expressing the ratio of width to length of watershed and is determined by dividing the area (sq. ft.) by the square of the length (ft.) of the watershed.

TABLE 2.--*Soil characteristics*

Location	Watershed	Surface texture	Subsoil permeability	Substratum permeability	Effective depth
Colorado Springs, Colo.	W–I	Moderately heavy	Moderate	Moderate	Deep
	W–II	Moderately light	Moderate to rapid	Moderate to rapid	Deep
	W–III	Medium	Moderate	Moderate	Deep
	W–IV	Moderately light	Slow	Moderate[1]	Shallow to moderate
Vega, Tex.	W–I	Moderately heavy	Slow	Moderate	Deep
	W–II	Moderately heavy	Slow	Moderate	Deep
	W–III	Light	Moderate to rapid	Moderate to rapid	Deep

[1]The substratum consists of materials from the Dawson Arkose formation.

TABLE 3.--*Vegetal cover*

Loca-tion	Water-shed	Type of cover	Dominant species	Basal density	Grazing and utilization
				%	
Colo-rado Spgs., Colo.	W-I	Cultivated	Wind stripped to rota-tion of corn, sorghum & grain	-	Winter-spring heavy
	W-II	Native Pasture	Blue grama, three awn & annuals	7½	Continuous heavy
	W-III	Native Pasture	Blue grama	8	Winter-spring heavy
	W-IV	Native Pasture	Blue grama, club moss & silver sage	16	Summer-Fall conservative
Vega, Tex.	W-I	Mixed cult. & pasture	Wheat following wheat on 50% of area. Blue grama, western wheat and annuals on uncultivated area.	-4	Winter light
	W-II	Native Pasture	Blue grama and buffalo	6	Continuous conservative
	W-III	Native Pasture	Blue grama, side-oats grama, yucca, and shrubs	3	Continuous conservative
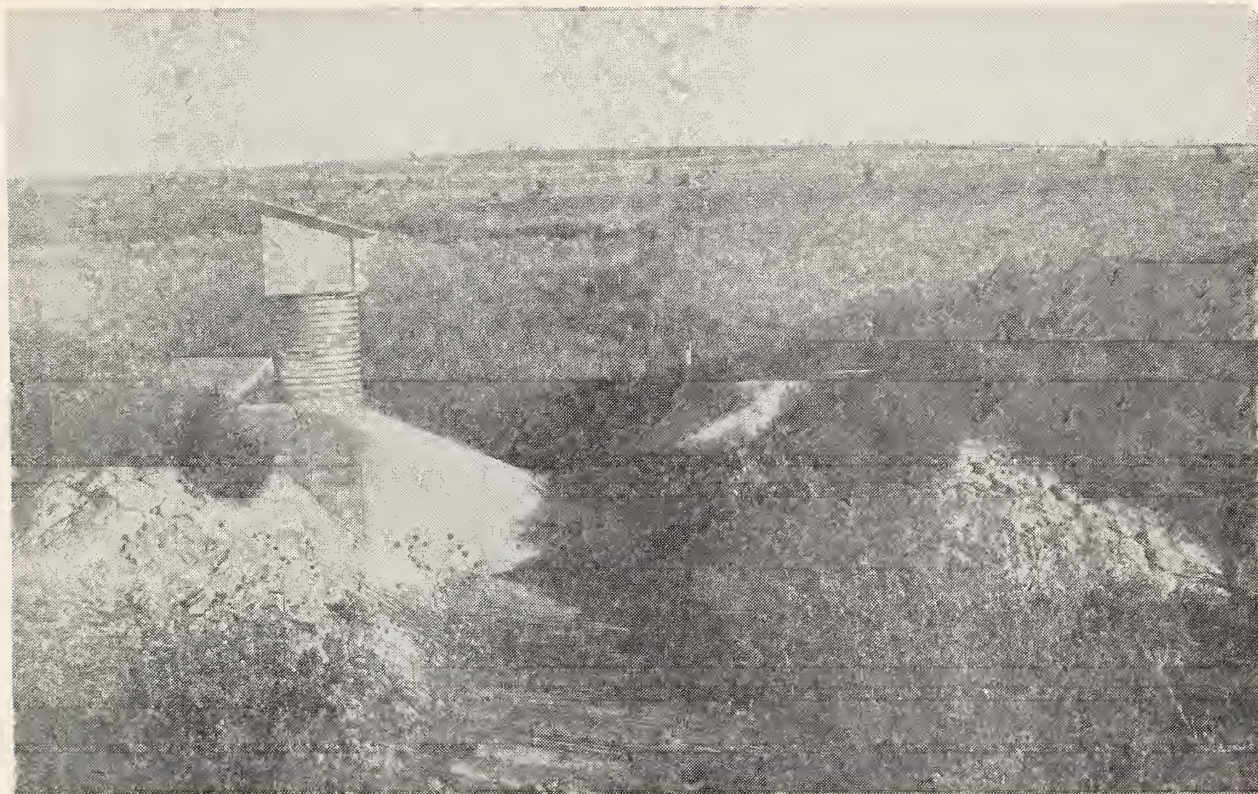
PLATE 1

A, General view of Watershed W-I, looking upstream, Colorado Springs, Colo.

B, General view of Watershed W-II, looking upstream, Colorado Springs, Colo.

PLATE 2

A, General view of Watershed W-III, looking upstream, Colorado Springs,Colo.
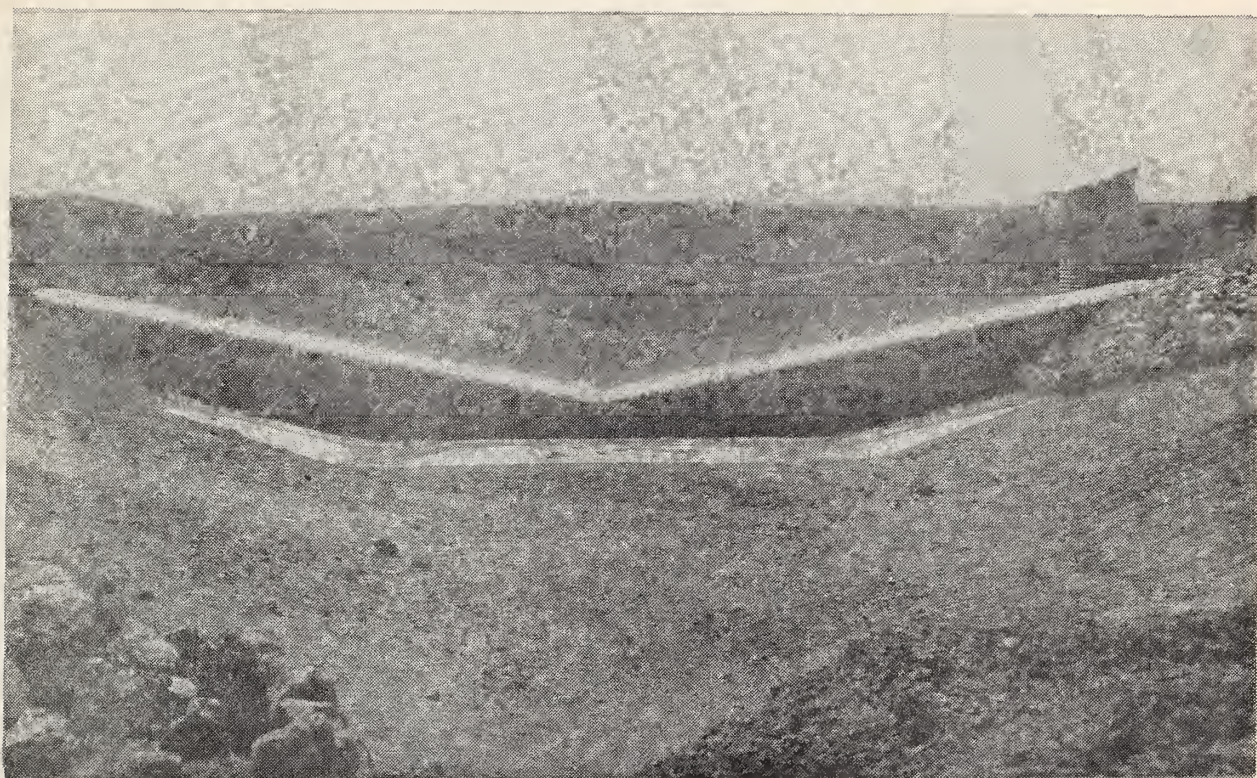
A, General view of Watershed W-I, looking upstream, Vega, Tex.

B, Watershed W-I, looking towards weir, Vega, Tex.

PLATE 4

A, General view of Watershed W-II, looking upstream, Vega, Tex.

B, Watershed W-III (left) looking upstream, Vega, Tex.

plots and also observations of the effects of natural precipitation on infiltration and run-off. This intensive work was continued until May 1942, when infiltrometer work was discontinued with the departure of Messrs. Sharp and Line to the armed forces. Observations of natural precipitation and its effects were continued until all of the work was discontinued on June 30, 1943.

This work included limited observations on Watershed W-IV at Colorado Springs, Colo. Before departing for the armed forces, Messrs. Sharp and Line completed a processed Progress Report (6).[2] The authors were fortunate in being able to observe this work closely as it proceeded and to participate in some phases of the investigations. The Progress Report and additional unpublished data have been consulted extensively in the preparation of this work.

Instrumentation and Collection of Records

Precipitation is measured in Fergusson weighing and recording rain and snow gages with a capacity of 9 inches of precipitation. These gages are geared so that 1 inch of the chart represents 0.67 inch of precipitation or 62 minutes of time. This permits readings of amounts of precipitation to the nearest 0.01 inch and of time to the closest minute. Each recording gage is accompanied by a United States Weather Bureau standard 8-inch non-recording gage which serves as a check. All watersheds at Vega, Tex., and all at Colorado Springs except watersheds W-I and W-III are equipped with two recording gages. Watersheds W-I and W-III at Colorado Springs are each equipped with one recording gage. Gages are regularly inspected and charts are changed once each week. In addition, inspections are made and charts are changed after every precipitation occurring between dates of regular inspection. Runoff is measured over triangular weirs of a type developed by the Soil Conservation Service and described in "Devices for Measuring Rates and Amounts of Runoff," SCS-TP-51. Side slopes of weirs are 2:1, 3:1, or 5:1 depending on the size of the watershed and the maximum rate to be measured. Each weir is provided with a stilling well containing a Friez type FW-1 water level recorder so geared that 1 inch of chart records 0.2 foot change in water level or 25 minutes of time. Water level can be read to the nearest 0.01 foot and time to the nearest minute. These instruments are regularly inspected and charts are changed once each week. They are also inspected after each precipitation occurring between regular inspections and charts are changed if runoff has been recorded.

Temperature and Relative Humidity are recorded on Friez hygrothermographs. Weather Bureau pattern maximum, minimum, and standard mercury thermometers installed in the same instrument shelter serve to check the records of temperature. The record of relative humidity is checked at each inspection, using a hand-aspirated psychrometer. The instruments are so geared that records may be read to the nearest degree, Fahrenheit, or the nearest percent of humidity, and to the nearest half-hour of time. Instruments are regularly inspected and charts changed once each week and inspections are made after every occurrence of precipitation. Two sets of instruments are installed to cover the four watersheds at Colorado Springs and one set for the watersheds at Vega, Tex.

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[2]/Italic numbers in parentheses refer to Literature Cited, p. 44.

Records are maintained for the several types of instruments as follows: Precipitation records show the date and time of beginning and ending of each rain or snow together with the amount of precipitation for the storm and day. For each rain amounting to 0.25 inch, or more, the record is compiled to show the amounts of rainfall occurring at different intensities. For each rain so compiled a record is made of the maximum amounts falling in various time intervals, 5, 10, 15, 20, and 30 minutes and 1, 2, 4, 6, and 12 hours. Runoff records are compiled to show the amounts of runoff for all runoff periods. Where the rates of runoff are appreciable, the record is compiled to show the rates of runoff for successive short intervals. Where the volume of water impounded is considerable in comparison with the area of the watershed, corrections are made for pondage. For each important runoff period a graphical record is plotted which includes, in addition to the hydrograph, a raingraph showing intensities of rainfall for the several periods of the storm and mass curves of the amounts of precipitation and runoff. These graphical records include a statement of the dates and times of occurrence of all rains during the 2-week period preceding runoff. Temperature and relative humidity records are compiled to include daily maximum, minimum, and mean temperatures and humidities.

In addition to the detailed records of storms and daily climate, summaries are maintained giving significant records or averages for months, seasons, or years.

Important changes in watershed conditions are recorded in the field by the observers and are summarized on cover and tillage maps. These records are supplemented by photographic records. At certain locations records of soil moisture conditions were maintained for several years. A continuous record of soil temperatures at depths of 2, 12, and 30 inches has been maintained at one location for nearly 8 years.

PART II. GENERAL DESIGN DATA

In the design of small structures, using the data contained herein, certain practical matters must be given consideration. Peak rates of runoff are tabulated for three different cover conditions; cultivated land, mixed cultivated and grassed land, and grassed land. The possibility of a change in land use from that existing at the time of planning to another which would result in higher peak rates cannot be overlooked. Changes in ownership may be followed by another entirely different type of farming. Even though the best use of which a piece of land is capable, without deterioration, may be designated as permanent pasture, changes in the economic relationships between products or the National welfare may require that the land be placed under cultivation for a time. Consequently, in selecting the proper table or figure for use in the design of a structure the land should be considered as cultivated, or mixed cultivated and grassed, if there appears to be a possibility that all or a portion of the drainage area may sometime be placed under cultivation.

For example, in designing a diversion on a pasture which is arable, it is advisable to design it for runoff from cultivated land rather than for that from grassed land. However, should the pasture be steep, rough, rocky, or stumpy, or be situated where rainfall is insufficient for crop production, it would not be reasonable to design the diversion on the basis of runoff from other than grassed land. In the case of structures on small watersheds, the small differences in peak rates of runoff resulting from considering land

in its possible rather than in its present cover condition usually result in changes in cost which are insignificant.

The results of analyses of the experimental data, tempered by such practical considerations, make it possible to arrive at rates of runoff to be considered in determining capacities of spillways, ditches, culverts, terrace-outlet channels, drop-inlet structures, and similar structures on small watersheds. Values for drainage areas ranging up to 200 acres are presented in tables 4 to 7, pages 14 to 17. Rates of runoff from larger areas are graphically represented in figures 2 to 5, pages 18 to 21.

The attention of users of the data presented in tables and figures is called particularly to the statements describing the conditions to which the values are applicable. Using these values in cases differing materially from those described would result in either too frequent failures or in uneconomical, wasteful design and render valueless the thought and effort expended in collecting, compiling, and publishing these data.

The values given in these tables and figures will probably be equaled or exceeded once in 25 years, on the average. It is well to emphasize the meaning of "expectancy" or "frequency" as used herein. When it is said that a peak rate of runoff is of a "25-year frequency" or has an "expectancy of 25 years," it does not mean that 25 years will elapse before the rate is equaled or exceeded. This may occur during the first year or in any other year of a 25-year period or even more than once in the period. It may not occur at all, but over a long period, such as 100 years, the rate will probably be equaled or exceeded four times. The same reasoning applies to 10-year or 50-year frequencies, indicating the probability of 10 or 2 occurrences in a century.

It is assumed that small structures on drainage areas not exceeding 200 acres ordinarily need not and should not be designed for values having expectancies greater than 25 years. In instances where the failure of a structure would release waters which would endanger life or result in extensive damage to property, values having expectancies of 50 years, or more, are justified. For such cases, to arrive at values with an expectancy of 50 years, multiply the values given in tables or figures by the coefficient given in the figures and marked for a 50-year frequency.

Similarly, for field structures such as diversions or terrace-outlet channels, it is probably sound economics to plan on repairing or replacing a smaller structure once in 10 years, on the average, rather than expend the additional money and labor required for a larger structure which would have to be repaired or replaced once in 25 to 50 years. For peak rates of runoff having an expectancy of 10 years, multiply the values in tables or figures by the coefficient given in the figures and marked for a 10-year frequency.

The following figures and tables (fig. 2, 3, 4, and 5, pp. 18 to 21, and tables 4, 5, 6, and 7, pp. 14 to 17) give values of rates of runoff for grassed land and mixed cultivated and grassed land for drainage areas up to 5,000 acres. For cultivated land, drainage areas are limited to 250 acres. As mentioned in the Introduction to Part I, prior to the inception of these runoff studies there were no records of stream flow originating in the High Plains from watersheds with drainage areas of less than 500 square miles. In extending the data obtained from watersheds of from 10 to 130 acres to larger areas, the author had no local records on which to base extrapolation. It was necessary to study the records of stream flow in other parts of the country where adequate records covering a wide range of drainage-area sizes were found.

TABLE 4.--*Rates of runoff for the design of conservation structures in the High Plains of Colorado and New Mexico*

IMPORTANT:--This table is applicable only for conditions closely resembling the following:

Topsoil texture--Cultivated land, Medium to Moderately Heavy
Grassed Land - - Medium
Subsoil permeability - - - - - - Moderate
Substratum permeability - - - - - Moderate
Effective depth of soil - - - - - Deep
Slope range--Cultivated land - - Level to 6%
Grassed land - - - - Rolling, up to 10%

Drainage area	Cover conditions				Drainage area	Cover conditions		
	Culti-vated	Mixed 50-50	Grass-land			Culti-vated	Mixed 50-50	Grass-land
acre	c.f.s.	c.f.s.	c.f.s.		acre	c.f.s.	c.f.s.	c.f.s.
2........	18	16	12		60........	231	198	148
4........	31	26	20		70........	258	221	165
6........	42	36	27		80........	284	243	182
8........	52	44	33		90........	309	265	198
10........	61	52	39		100........	334	286	214
12	70	60	45		110........	358	306	229
14........	79	68	51		120........	381	326	244
16........	87	75	56		130........	404	346	259
18........	95	81	61		140........	427	366	273
20........	102	88	65		150........	449	385	288
25........	121	104	77		160........	471	403	301
30........	139	119	89		170........	492	421	315
35........	155	133	99		180........	512	438	328
40........	171	146	109		190........	532	456	341
45........	187	160	120		200........	551	472	353
50........	202	173	129					

Note: 'Mixed, 50-50,'refers to watersheds partly cultivated and partly in grass in approximately equal proportions.

Values given in these tables will probably be equaled or exceeded once in 25 years.

For values having 50-year expectancies, multiply these values by:
Cultivated land, 1.15   Grassed land, 1.18

For values having 10-year expectancies, multiply these values by:
Cultivated land, 0.82   Grassed land, 0.77

TABLE 5.--*Rates of runoff for the design of conservation structures in the High Plains of Colorado and New Mexico*

IMPORTANT:--This table is applicable only for conditions closely resembling the following:

Topsoil texture--Cultivated land, Moderately Light to Medium
Grassed land - - Moderately Light
Subsoil permeability - - - - - - Moderate to Rapid
Substratum permeability - - - - - Moderate to Rapid
Effective depth of soil - - - - - Deep
Slope range--Cultivated land, - - Level to 5%
Grassed land, - - - Rolling, up to 10%

Drainage area	Cover conditions			Drainage area	Cover conditions		
	Culti-vated	Mixed 50-50	Grass-land		Culti-vated	Mixed 50-50	Grass-land
Acre	*c.f.s.*	*c.f.s.*	*c.f.s.*	*Acre*	*c.f.s.*	*c.f.s.*	*c.f.s.*
2.........	18	16	14	60	225	207	177
4.........	30	27	23	70	251	231	197
6.........	40	37	32	80	277	255	217
8.........	50	46	39	90	301	277	236
10.........	59	55	47	100	325	299	255
12.........	68	63	54	110	348	320	273
14.........	77	71	60	120	371	341	291
16.........	85	78	67	130	393	362	309
18.........	92	85	72	140	415	383	326
20.........	100	92	78	150	437	402	343
25.........	118	108	92	160	458	422	360
30.........	135	124	106	170	478	441	376
35.........	151	139	119	180	498	459	391
40.........	166	153	131	190	518	477	407
45.........	182	167	143	200	536	494	421
50.........	196	181	154				

Note: 'Mixed, 50-50,' refers to watersheds partly cultivated and partly in grass in approximately equal proportions.

Values given in these tables will probably be equaled or exceeded once in 25 years.

For values having 50-year expectancies, multiply these values by:
Cultivated land, 1.15   Grassland, 1.18

For values having 10-year expectancies, multiply these values by:
Cultivated land, 0.82   Grassed land, 0.77

TABLE 6.--*Rates of runoff for the design of conservation structures in the High Plains of Colorado and New Mexico*

IMPORTANT:--This table is applicable only for conditions closely resembling the following:

      Topsoil texture--Cultivated land, Moderately Light
                       Grassed land - - Moderately Light
      Subsoil permeability - - - - - - Slow
      Substratum permeability - - - - - Moderate
      Effective depth of soil - - - - - Shallow to Moderate
      Slope range -- Cultivated land - Level to 2%
                     Grassed land - - - Rolling, up to 20%

WARNING:--Use of this table must be limited to soils in Central Colorado developed from materials of the Dawson Arkose formation.

Drainage area	Cover conditions			Drainage area	Cover conditions		
	Culti-vated	Mixed 50-50	Grass-land		Culti-vated	Mixed 50-50	Grass-land
Acre	c.f.s.	c.f.s.	c.f.s.	Acre	c.f.s.	c.f.s.	c.f.s.
2........	19	17	13	60........	241	212	170
4........	32	28	22	70........	269	237	190
6........	43	38	31	80........	296	261	209
8........	54	47	38	90........	322	284	227
10........	63	56	45	100........	348	306	245
12........	73	65	52	110........	373	328	263
14........	82	73	58	120........	397	350	280
16........	91	80	64	130........	422	371	297
18........	99	87	70	140........	445	392	314
20........	107	94	75	150........	468	412	330
25........	126	111	89	160........	491	432	346
30........	144	127	102	170........	512	451	361
35........	162	142	114	180........	534	470	376
40........	178	157	126	190........	555	489	391
45........	195	171	137	200........	575	506	405
50........	210	185	148				

Note:--'Mixed, 50-50,' refers to watersheds partly cultivated and partly in grass in approximately equal proportions.

Values given in these tables will probably be equaled or exceeded once in 25 years.

For values having 50-year expectancies, multiply these values by:
        Cultivated land, -1.15   Grassland, -1.18

For values having 10-year expectancies, multiply these values by:
        Cultivated land, -0.82   Grassland, -0.77

TABLE 7.--*Rates of runoff for the design of conservation structures in the High Plains of Colorado and New Mexico*

IMPORTANT:--This table is applicable only for conditions closely resembling the following:

Topsoil texture--Cultivated land, Moderately heavy
                         Grassed land - - Moderately heavy
Subsoil permeability - - - - - - Slow
Substratum permeability - - - - - Moderate
Effective depth of soil - - - - - Deep
Slope range--Cultivated land - - Level to 2%
                   Grassed land - - - - Rolling, up to 18%

NOTE: This table is designed for use on those characteristic watersheds where rolling grassed lands lie below comparatively level cultivated fields or grassed lands, as in the 'breaks' country.

Drainage area	Cover conditions				Drainage area	Cover conditions		
	Culti-vated	Mixed 50–50	Grass-land			Culti-vated	Mixed 50–50	Grass-land
Acre	*c.f.s.*	*c.f.s.*	*c.f.s.*		*Acre*	*c.f.s.*	*c.f.s.*	*c.f.s.*
2........	16	14	13		60........	206	183	164
4........	27	24	22		70........	231	205	183
6........	37	33	30		80.......	254	225	202
8........	46	41	37		90........	276	245	219
10........	54	48	43		100........	298	264	237
12........	63	56	50		110........	320	283	254
14........	71	63	56		120........	340	302	270
16........	78	69	62		130........	361	320	287
18........	85	75	67		140........	382	338	303
20........	91	81	73		150........	401	356	319
25........	108	96	86		160........	420	373	334
30........	124	110	98		170........	439	389	349
35........	139	123	110		180........	457	405	363
40........	153	135	121		190........	475	421	378
45........	167	148	133		200........	492	436	391
50........	180	160	143					

Notes: 'Mixed, 50-50,' refers to watersheds partly cultivated and partly in grass in approximately equal proportions.

Values given in these tables will probably be equaled or exceeded once in 25 years.

For values having 50-year expectancies, multiply these values by:
       Cultivated land, -1.20   Grassland, -1.18

For values having 10-year expectancies, multiply these values by:
       Cultivated land, -0.80 .   Grassland, -0.77

RATES OF RUNOFF FOR THE DESIGN OF CONSERVATION STRUCTURES
IN THE
HIGH PLAINS OF COLORADO AND NEW MEXICO

IMPORTANT:- This figure is applicable only for conditions
closely resembling the following:

Topsoil texture — Cultivated land, Medium to Moderately Heavy
Grassed land   Medium
Subsoil permeability   Moderate
Substratum permeability   Moderate
Effective depth of soil   Deep
Slope range — Cultivated land   Level to 6%
Grassed land   Rolling, up to 10%

Values indicated by these curves will probably be equaled
or exceeded once in 25 years.
For values having 50-year expectancies, multiply by:
Cultivated Land, 1.15
Grassed Land, 1.18
For values having 10-year expectancies, multiply by:
Cultivated Land, 0.82
Grassed Land, 0.77

Mixed Cultivated and Grassed Land is assumed to be divided about equally

Mixed Cultivated and Grassed Land

Grassed Land

DRAINAGE AREA (acres)

RATE OF RUNOFF (cubic feet per second)

Cultivated Land

Mixed Cultivated and Grassed Land

Grassed Land

DRAINAGE AREA (acres)

RATE OF RUNOFF (cubic feet per second)

Figure 2

SOIL CONSERVATION SERVICE, WASHINGTON, D.C., 1947

RATES OF RUNOFF FOR THE DESIGN OF CONSERVATION STRUCTURES

IN THE

HIGH PLAINS OF COLORADO AND NEW MEXICO

IMPORTANT:- This figure is applicable only for conditions
closely resembling the following:

Topsoil texture—Cultivated land, Moderately Light to Medium
                  Grassed land   Moderately Light
Subsoil permeability   Moderate to Rapid
Substratum permeability   Moderate to Rapid
Effective depth of soil   Deep
Slope range— Cultivated land   Level to 5%
             Grassed land   Rolling, up to 10%

Values indicated by these curves will probably be equaled
or exceeded once in 25 years.
For values having 50-year expectancies, multiply by:
                  Cultivated Land, 1.15
                  Grassed Land, 1.18
For values having 10-year expectancies, multiply by:
                  Cultivated Land, 0.82
                  Grassed Land, 0.77

Mixed Cultivated and Grassed Land

←Grassed Land

Mixed Cultivated and Grassed Land is assumed to be divided about equally

DRAINAGE AREA (acres)

RATE OF RUNOFF (cubic feet per second)

Cultivated Land→

←Mixed Cultivated and Grassed Land

←Grassed Land

DRAINAGE AREA (acres)

RATE OF RUNOFF (cubic feet per second)

Figure 3

SOIL CONSERVATION SERVICE, WASHINGTON, D.C., 1947

RATES OF RUNOFF FOR THE DESIGN OF CONSERVATION STRUCTURES
IN THE
HIGH PLAINS OF COLORADO AND NEW MEXICO

IMPORTANT:- This figure is applicable only for conditions
closely resembling the following:

Topsoil texture – Cultivated land,	Moderately Light
Grassed land	Moderately Light
Subsoil permeability	Slow
Substratum permeability	Moderate
Effective depth of soil	Shallow to Moderate
Slope range – Cultivated land	Level to 2%
Grassed land	Rolling, up to 20%

WARNING: Use of this figure must be limited to soils in
Central Colorado developed from materials of
the Dawson Arkose formation.

Values indicated by these curves will probably be equaled
or exceeded once in 25 years.
For values having 50-year expectancies, multiply by
Cultivated Land, 1.15
Grassed Land, 1.18
For values having 10-year expectancies, multiply by
Cultivated Land, 0.82
Grassed Land, 0.77

Mixed Cultivated and Grassed Land is assumed to be divided about equally.

RATE OF RUNOFF (cubic feet per second)

Grassed Land

Mixed Cultivated and Grassed Land

ORAINAGE AREA (acres)

Cultivated Land

Mixed Cultivated and Grassed Land
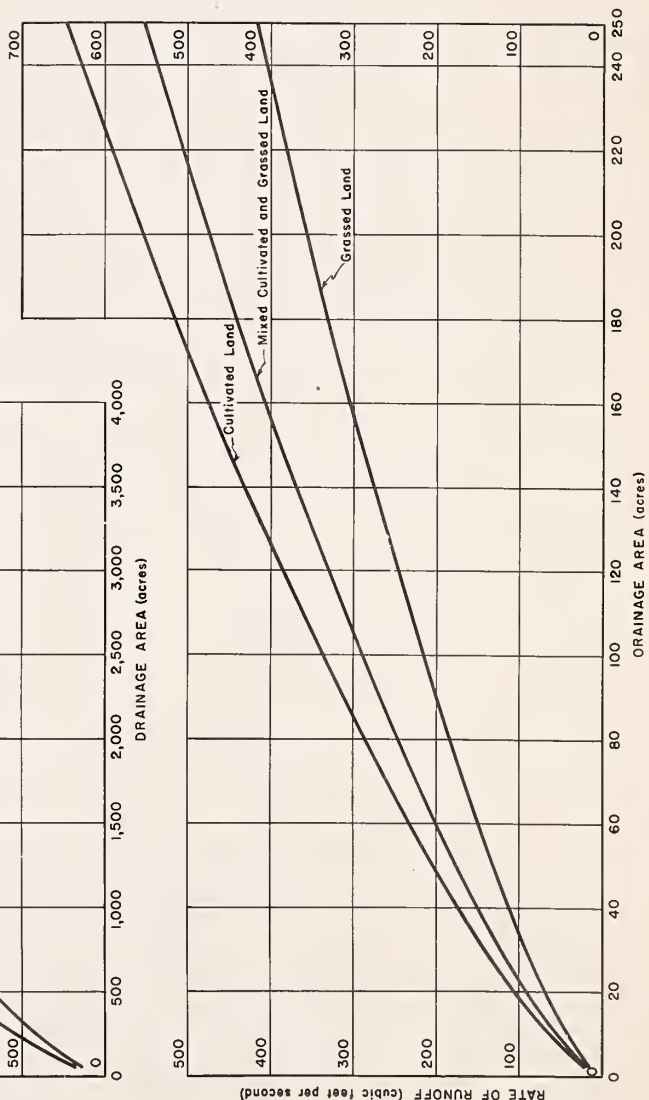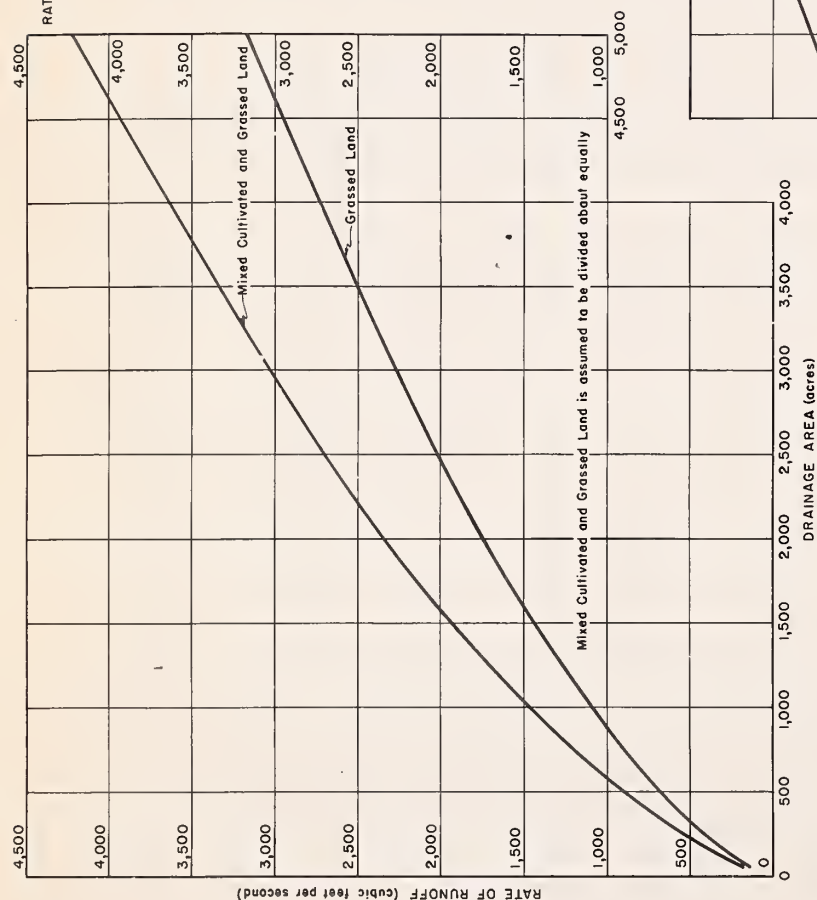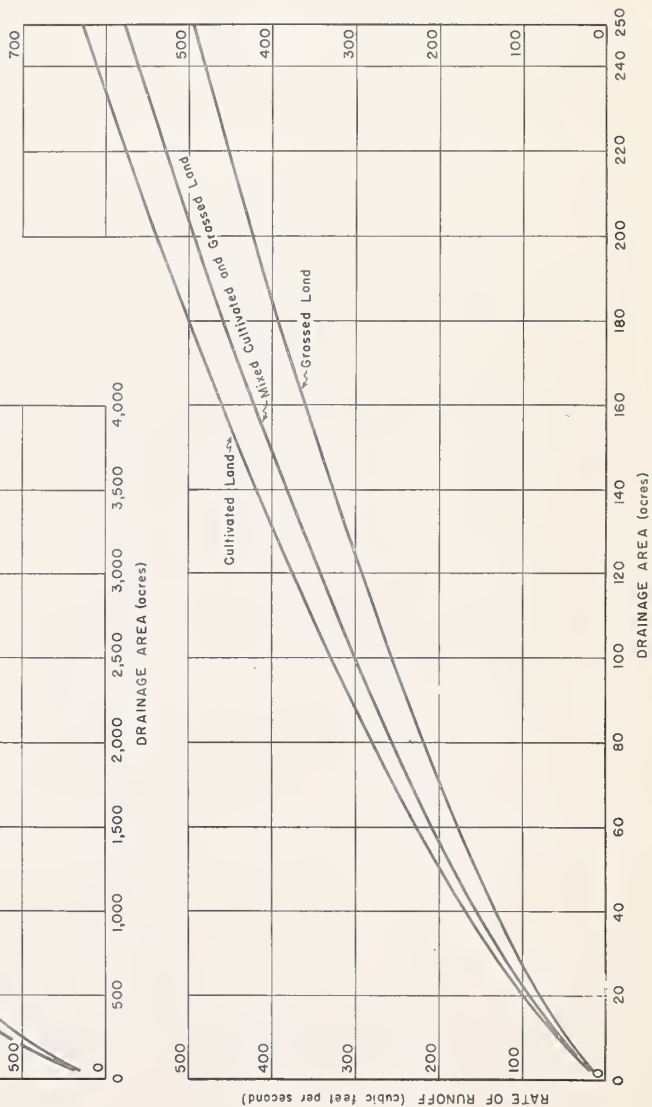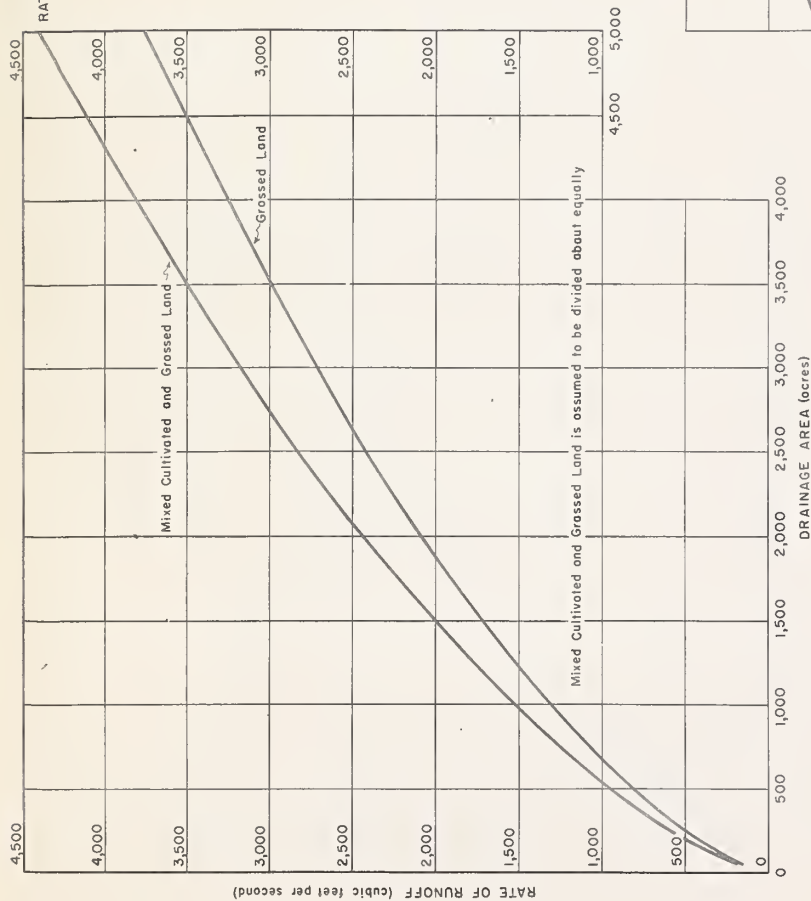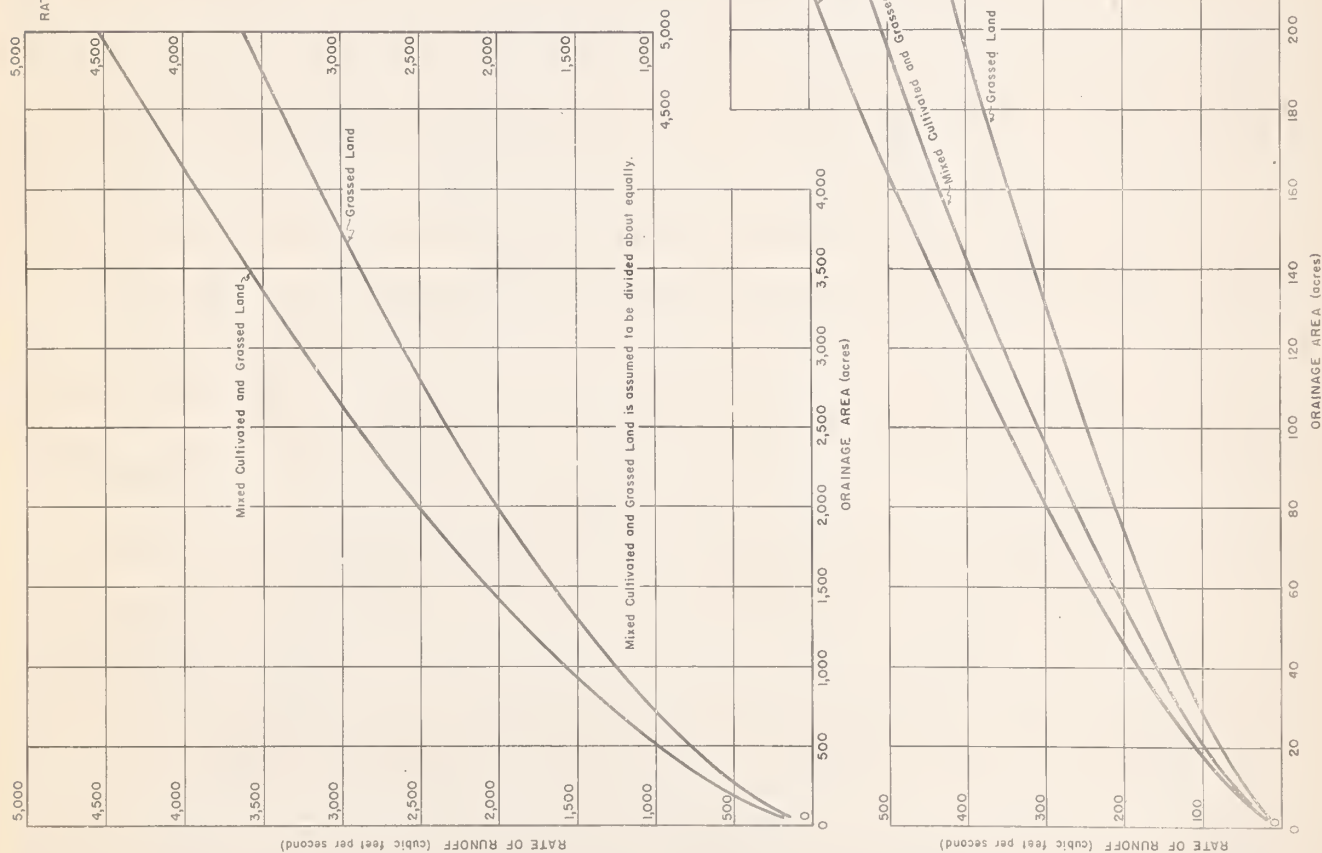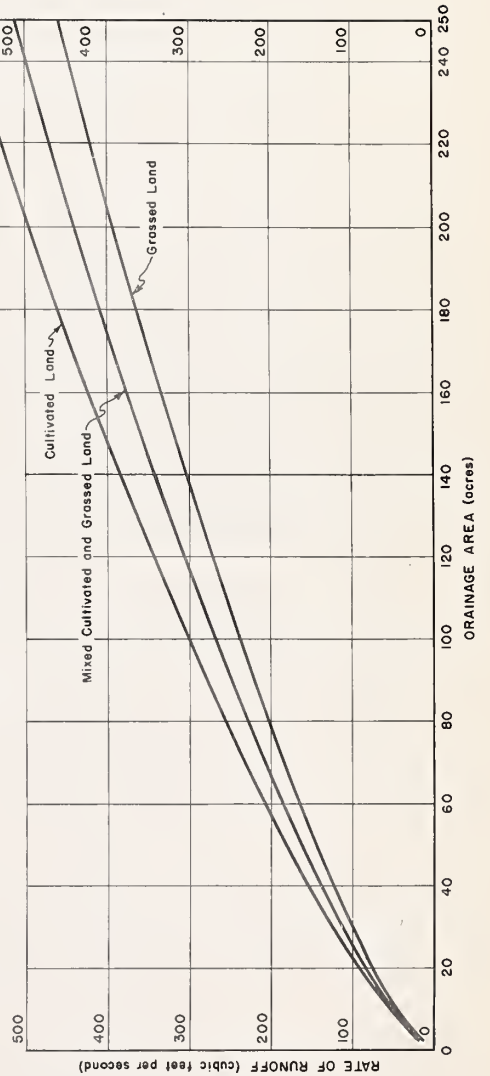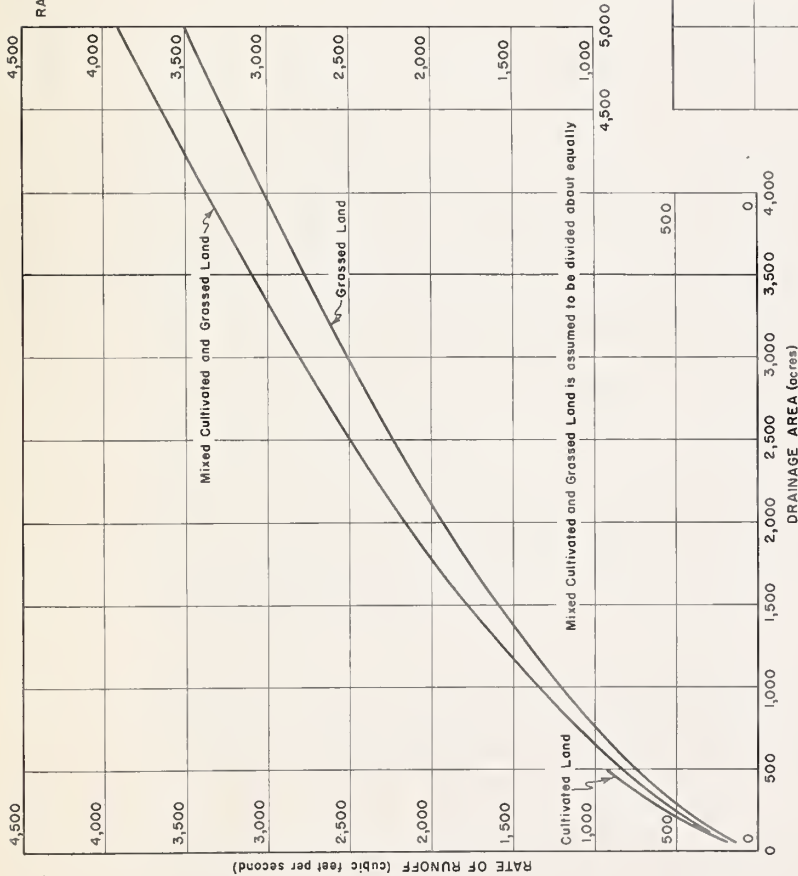
Grassed Land

RATE OF RUNOFF (cubic feet per second)

ORAINAGE AREA (acres)

Figure 4

RATES OF RUNOFF FOR THE OESIGN OF CONSERVATION STRUCTURES
IN THE
HIGH PLAINS OF COLORAOO AND NEW MEXICO

Figure 5

SOIL CONSERVATION SERVICE WASHINGTON,D.C.,1947

In selecting the basis on which the values given in these tables and figures were calculated, consideration was given to all of the physiographic features, such as slope, shape of watershed, channel conditions, etc. Consideration was also given to amounts of precipitation which occurred during critical seasons and to the frequency of the occurrence of excessive rainfall. Groups of watersheds having reasonably similar characteristics were found. Adjustments were made in their records to allow for the differing conditions in the High Plains. The basis used in calculations is believed conservative and the results are considered as on the safe side. As mentioned in the Foreword, revision in these values will be desirable when more extensive records become available and methods of analysis are improved.

PART III. FACTORS INFLUENCING PEAK RATES OF RUNOFF

Introduction

An evaluation of all of the factors influencing peak rates of runoff is scarcely possible from the information thus far developed by investigators. Certain factors, such as topography, are quite stable. Others, such as soils and infiltration undergo diurnal and seasonal fluctuations and are influenced by the condition of vegetative cover. The state of the vegetative cover, in turn, is subject to many factors, some as remote as economic conditions or political policies. In this chapter, some mention will be made of the more important considerations influencing peak rates of runoff from small watersheds. Where the runoff studies investigations have yielded data illustrative of the effects of changes in these factors, the discussion will be more extensive than where only theoretical considerations, without experimental confirmation, are involved.

The Runoff Process--Definitions

Before undertaking this discussion, a brief description of the more important processes involved in runoff, together with a definition of terms, may be helpful. As rain falls to the ground, a portion strikes the leaves of the stems of the vegetation and clings to the surfaces or is caught in the cups where leaves join stems or is soaked up by the litter on the ground. This is known as canopy interception or simply as interception and its quantity is expressed as the equivalent depth in inches over the entire area being considered. Once the capacity of the vegetation to hold water is reached, no further loss occurs from this source. Of the water reaching the surface of the soil, the first portion is absorbed into the soil. This is called infiltration and continues at a rate, at first rapid, then gradually diminishing and tending to become constant. The rate of infiltration is expressed in terms of inches of water entering the soil over the entire area being considered, or simply as inches per hour.

When the rate at which rainfall water reaches the soil is greater than the rate at which it is being absorbed by the soil, a film or layer of water forms over the surface. This is known as surface detention and is measured by its average depth in inches. As the depth or thickness of this layer increases, sufficient head is developed to start movement over the surface toward lower elevations. This is called overland flow and the rate of movement is often expressed in inches per minute or may be expressed in feet per second. This overland flow at first accumulates in the natural small depressions which exist on all surfaces and forms numerous small, shallow pools. The amount

of water retained in these pools is called <u>depression storage</u> and is expressed as the e-quivalent depth in inches over the entire area being considered. When once these depressions are filled, there is no further loss from this source.

Runoff, therefore, is a residual. After the requirements of interception and depression storage[3]/ are satisfied, the only appreciable loss is by infiltration. The rate of runoff from any spot then becomes equal to the rate (intensity) of precipitation minus the rate of infiltration.

The rest of the overland flow continues down the slope, at first forming tiny rills which form a converging network of small, unstable channels. Proceeding down the slope, the multiplicity of rills continue to converge, increasing in depth and velocity, until a well-defined channel is reached. Here, overland flow unites with the water in the channel. The depth of flow is, comparatively, much greater and a material acceleration in velocity occurs. This is known as <u>channel flow</u> and its velocity is usually measured in feet per second and the rate of flow expressed in cubic feet per second. This may be converted into inches of water over the entire contributing area per hour or, simply, inches per hour. This latter form of expression is helpful in that it conforms with the measurements used for the other terms and simplifies comparisons.

It must be recognized that channel flow, particularly in watercourses with large drainage areas, is made up of two elements. These are the water that flows over the surface of the ground, and <u>subsurface flow</u> which emerges from the banks or bed of the channel. This subsurface flow consists of a portion of the water which has been absorbed by the soil and moved through it to a point where contact with a less permeable material has forced it to the surface. In some locations with thin, readily permeable soils underlain by impermeable material, this subsurface flow or runoff may constitute a major portion, even substantially all, of the channel flow and, of course, have a profound influence on peak rates of runoff. For the comparatively small watersheds and the conditions being considered in the High Plains of Colorado and New Mexico the effect of subsurface flow on peak rates is of small importance, although it frequently does have a large effect on the total amount of runoff. This is due to the slow rate at which subsurface flow moves through the soils encountered making it unlikely that any appreciable portion will emerge into channels until after the peak rate of runoff has been passed. It must be remembered that a normal characteristic of the runoff-producing rains of the area is that maximum intensities are reached near the beginning of the storm and that intensities of rainfall diminish rapidly as the storm continues.

Channel flow moves down the watercourse impeded by roughness of the channel and by vegetation. Narrowing of the channel restricts movement and may cause the water to back up to an appreciable depth, or a change to a flatter slope may reduce velocity and cause the stream to widen. All such changes result in accumulations along the length of the watercourse which, taken together, are known as <u>channel storage.</u>

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[3]/This discussion omits consideration of minor losses, such as evaporation from the soil surface or transpiration by plants during rainfall, adhesion to the soil, etc., as negligible in their effects on peak rates of runoff from small watersheds.

The differences between "overland flow" and "channel flow" are marked. Overland flow begins when the accumulation of water on a surface reaches a depth sufficient for gravity to start the downward movement. This water quickly forms into tiny rills of varying depths and widths, moving in unstable channels at slow velocities. As the tiny rill proceeds down the slope it is joined by additional water and the increased volume sooner or later causes the rill to overflow or widen. It merges with other rills to form a combined flow somewhat deeper and moving at a higher velocity. These flows are retarded by the roughness of the ground surface, by the obstruction offered by stems and other vegetation, and by accumulations of litter. These retarding effects are large in comparison with the depth of flow, and movement is at a low, though accelerating rate. The process of overflow and merging continues until a well-defined, stable channel is reached. Channel flow is the movement of an accumulated volume of water of appreciable depth down a more-or-less well-defined watercourse. This flow is impeded and retarded by the same factors as overland flow but their effects are small in comparison with depth of flow and movement may be rapid. A crude illustration of the order of magnitude of the two velocities of flow is that overland flow is often measured in inches per minute while channel flow is customarily measured in feet per second, a unit 720 times as great.

The movement of a particle of runoff water from the most remote to the lowest point of a watershed is a combination of overland and channel flows and the time required for this movement is known as the period or time of concentration. Under runoff-producing rainfall, continuing at a constant rate, the time of concentration measures the time which must elapse before all portions of a watershed begin to contribute to runoff and the maximum rate of runoff is recorded.

Unfortunately, the time of concentration of a watershed is not a fixed characteristic, such as slope or form factor, but is a variable, dependent upon vegetal cover and surface conditions and even on the intensity of rainfall. Nevertheless, the concept of a time of concentration is helpful in understanding the effects which changes in conditions have upon runoff.

Intensity of Rainfall

The rate at which rainfall water is supplied to a watershed is the limiting factor of peak rates of runoff in the High Plains of Colorado and New Mexico. In this area, winter precipitation is light and the amount of snow cover subject to melting under the influence of warm spring rains does not have the significance in connection with the peak rates of runoff that it may assume in other portions of the country. During the period of record of the runoff studies at Colorado Springs and Vega, Tex., peak rates of runoff which have occurred as a result of melting snow or of rain falling on snow-covered watersheds have been negligible.

The intensities of rainfall which may be expected are highly variable, changing with the season, the location, and the duration of the period considered. The occurrence of

storms which the United States Weather Bureau classes as <u>excessive rainstorms</u>[4]/ is essential for the production of peak rates of runoff. Yarnell (8) determined that the number of excessive rainstorms occurring in the High Plains of Colorado and New Mexico varied from zero in the winter months to a maximum in mid-summer. For a location at the southeast corner of the State of Colorado, his diagrams show the average number of excessive storms to be expected for the various months to be as indicated in table 8, page 26. These diagrams show that values for this location are, in general, as great as any that may be expected anywhere in the area. Yarnell's values are roughly confirmed by the records obtained by the runoff studies at Colorado Springs and Vega, Tex., which are shown with Yarnell's values in the table. The larger variation of the Vega record is accounted for by the brevity of the record, 6 years, which included 1 year of extremely heavy precipitation. From this table it will be noted that runoff-producing rains are not to be expected during the 5-month period, November through March, and but occasionally in April and October. In the 9-year record at Colorado Springs, no excessive rainstorm has occurred earlier than May 10 or later than September 30. At Vega, Tex., the earliest date of occurrence in a 6-year record is April 4 and the latest is October 25. In Colorado Springs, 83 percent of all excessive rainstorms occurred during the months of June, July, and August, while at Vega, Tex., 67 percent occurred during these months.

Maximum intensities of precipitation vary with location. Yarnell (8) indicates a general trend of increasing intensities to be expected from the western limit of the High Plains, adjacent to the mountains, to the eastern boundaries of the States of Colorado and New Mexico. The rate of increase is not uniform for time intervals or for frequencies, but, through the range of intervals applicable to small watersheds and the range of frequencies considered, the deviations from the average are believed to be less than the local effects of topography and cover on the convective storms which provide intense rainfall. On this basis, the author has used the average value of 8 percent per degree of longitude as a measure of the increase in intensity from the western limit of the High Plains to the eastern boundaries of the two States.

The maximum intensities of precipitation throughout the High Plains display large variations with changes in the length of the time interval being considered. Yarnell (8) shows for the southeast corner of the State of Colorado a 25-year frequency rate of 6.72 inches per hour for a 5-minute interval, 2.25 inches per hour for a 1-hour interval, and but 0.18 inch per hour for a 24-hour interval. The rapidity of the change in intensity of rainfall with change in length of the interval is indicated by the curve in figure 6, page 27. This curve is typical of the trend of decrease in intensity with increase in the time interval irrespective of the frequency being considered or the location within the area.

4/Excessive precipitation is defined by the U. S. Weather Bureau as follows: Precipitation is considered excessive when it equals or exceeds at least one of the amounts given for the periods named below:

5 minutes	0.25 inch	25 minutes	0.45 inch	45 minutes	0.65 inch
10 "	.30 "	30 "	.50 "	50 "	.70 "
15 "	.35 "	35 "	.55 "	55 "	.75 "
20 "	.40 "	40 "	.60 "	60 "	.80 "

TABLE 8.--*Number of excessive rainstorms by months*

Month	S.E.corner of Colorado	Location Colorado Springs	Vega, Tex.
January	0	0	0
February	0	0	0
March	0	0	0
April	.17	0	.50
May	.33	.17	.58
June	.67	.28	1.03
July	1.00	1.56	.86
August	.67	1.31	1.53
September	.33	.17	.31
October	.13	0	.46
November	0	0	0
December	0	0	0
Total	3.30	3.49	5.27
Source of data	Yarnell	Runoff studies	Runoff studies
Length of record	30 + years	9 years	6 years

Values for Yarnell are transcribed from U. S.
Dept. of Agriculture Misc. Publication 204.
Values for Colorado Springs and Vega, Tex., are
each the average of the records obtained from six
recording gages.

INTENSITY OF PRECIPITATION

To be Expected Once in 25 Years
at the
South-east Corner of the State of Colarada

Based an Rainfall Intensity-Frequency Data
by David L. Yarnell

U.S. Department of Agriculture
Miscellaneous Publication No. 204

Intensity of Precipitation – Inches per hour

Time Interval – Hours
One inch equals 24 minutes
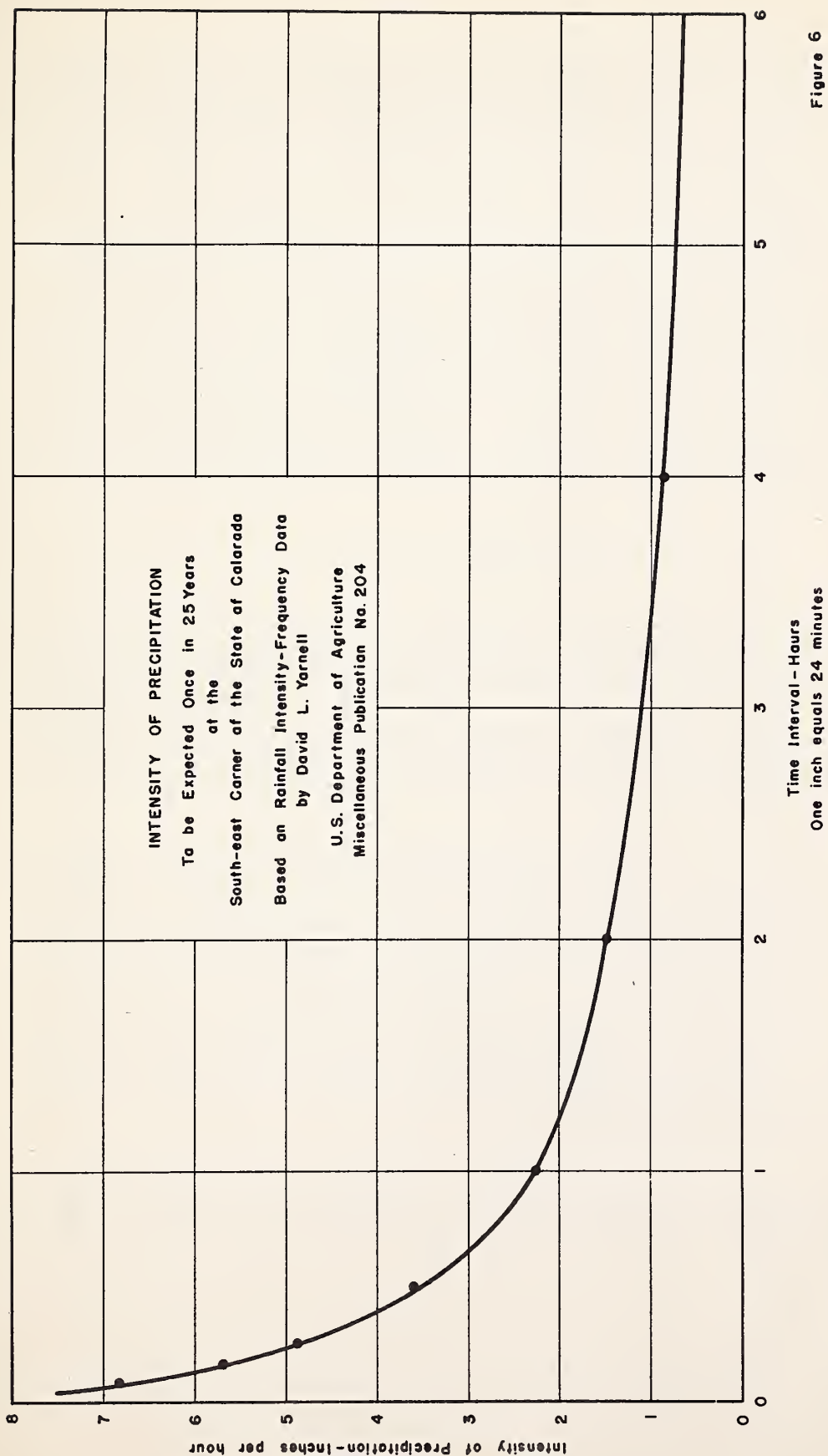
Figure 6

SOIL CONSERVATION SERVICE, WASHINGTON, D.C., 1947

Estimates of the intensities of precipitation to be expected once in 25 years, using the 9-year record at Colorado Springs based on the average of six recording rain gages yield rates 7 percent to 18 percent higher than indicated on Yarnell's charts for time intervals up to 1 hour. Similar estimates using the 6-year record at Vega, Tex., also based on the average of six gages, yield rates 10 percent to 16 percent higher than Yarnell for time intervals of 5, 10, and 15 minutes but 4 percent to 10 percent lower for intervals of 30 minutes and 1 hour. These variations from Yarnell's estimates are moderate and of limited significance in view of the much wider variations in probable rates indicated by individual gages. Comparison of the highest with the lowest probable rate estimated for a given time interval from gages in the same group shows excesses in the general order of 50 percent and individual cases where the excess is 100 percent. This analysis of observed data should tend to increase confidence in the general applicability of the data presented by Yarnell (8) for the High Plains. It should also cause more general recognition of the fact that purely local conditions of topography and cover may induce local concentrations of precipitation with intensities considerably greater than those generally experienced over the area. Such local concentrations ordinarily have little effect on large watersheds but may be important when considered in connection with small watersheds.

Topography

Slope

The principal effect of slope is on the velocity of flow and, as a result, on time of concentration. Investigations by Spencer, Kimball, and Kellogg (7) on sprinkled plots, including a broad range of the more common soil types of the High Plains of Colorado, showed no significant increase in the rate of runoff under a constant rate of simulated rainfall through a range of slopes of 1 percent to 10 percent. With the total discharge, Q, remaining constant, any increase in velocity, v, must be accompanied by a decrease in the cross section of the water flowing, a, and consequently in the depth of flow, d, and the hydraulic radius, r.

The mechanics of overland flow has not been as thoroughly investigated as that of channel flow and there exists some question whether the generally accepted formulas for channel flow are entirely applicable. However, to obtain a measure of the general effect of slope on velocity, seeking relative information rather than precise values, the use of these formulas is permissible and that of Manning (4) lends itself particularly well to this purpose. Since overland flow may be considered as occurring over an indefinitely wide surface, the hydraulic radius, r, is the same as the depth, d. Similarly, in the High Plains, much of the channel flow occurs in wide, flat, vertical banked sand washes, and the hydraulic radius is approximately equal to the mean depth. Considering unit width of flow, the following demonstration is equally applicable to both types of flow. When a unit width of flow is considered, the area of the water flowing is one d, or simply d, which is substantially equal to r.

Manning's formula, $Q = 1.486 \, a \, r^{2/3} \, s^{1/2} / n$, where n is the coefficient of roughness and s, the slope of the water surface, may be written for unit width of flow as:

$$Q = 1.486 \, r^{5/3} \, s^{1/2} / n.$$

Since with all other conditions remaining constant, Q remains constant within the ordinary limits of slope, the change in hydraulic radius r for a change in slope represented by the coefficient k may be determined by equating the two expressions for Q as follows:

$$Q_1 = 1.486 \; r_1^{5/3} \; s_1^{1/2} /n$$

and

$$Q_2 = 1.486 \; r_2^{5/3} \; s_2^{1/2} /n$$

but $s_2 = ks_1$

so

$$Q_2 = 1,486 \; r_2^{5/3} (ks_1)^{1/2} /n$$

since $Q_1 = Q_2$

$$1.486 \; r_1^{5/3} \; s_1^{1/2} /n = 1.486 \; r_2^{5/3} \; (ks_1)^{1/2} /n$$

$$r_2^{5/3} = r_1^{5/3}/k^{1/2}$$

$$r_2 = (1/k^{1/2})^{3/5} \; r_1 = r_1/k^{0.3} = r_1 k^{-0.3}$$

since $Q = av$ or, for this case, $Q = rv$

$$r_1 v_1 = r_2 v_2$$

$$v_2 = v_1 r_1 /r_2 = v_1 r_1 /r_1 k^{-0.3} = k^{0.3} v_1$$

Using these formulas, a 20 percent increase in slope (k = 1.20) would result in an increase of approximately $5\frac{1}{2}$ percent in velocity. A 100 percent increase in slope (k = 2.00) would result in an increase of approximately 23 percent in mean velocity.

With the average velocity throughout the watershed changing by $k^{0.3}$, the time of concentration would also be changed and the new time of concentration would equal the old multiplied by the factor $k^{-0.3}$. Thus, an increase of 20 percent in slope would result in a new time of concentration approximately 5 percent less than before, or an increase of 100 percent in slope would change the time of concentration to one approximately 19 percent less. Consequently, the time interval to be used in determining the appropriate intensity of precipitation applicable to the steeper watersheds will be less and the intensity of precipitation will be greater. Referring to figure 6, page 27, using the 5 percent reduction in time interval applicable to a 20 percent increase in slope, for a small watershed with a 10-minute period of concentration, the increase in intensity of precipitation would be about 0.11 inch per hour or 2 percent. For a larger watershed with a 1-hour period of concentration the increase would be about 0.08 inch per hour or $3\frac{1}{2}$ percent while for a still larger watershed with a 4-hour period of concentration, the increase would be about 0.04 inch per hour or $4\frac{1}{2}$ percent. Using the 19 percent reduction in time of concentration for a 100 percent increase in slope, corresponding figures would be: For the 10-minute period, 0.42 inch per hour or 7 percent; for the 1-hour period, 0.37 inch per hour or 17 percent; for the 4-hour period, 0.16 inch per hour or 19 percent. It will be noted that the amount of increase in the intensity of precipitation decreases as the time interval becomes longer but that the percentage of the increase becomes greater.

As shown in the discussion of the runoff process, runoff is a residual, and percentage proportions cannot be applied to rates of runoff to adjust for changes in intensity of precipitation. The entire amount of the increase in the intensity of precipitation will be reflected by a like increase in the rate of runoff. To evaluate the effect of increase in slope further, additional assumptions must be made to relate the time of concentration with the size of watershed. Since the time of concentration of a watershed depends upon the relative proportions of overland flow at a slow rate and channel flow at a much more rapid rate, each watershed will have its own individual time of concentration for each combination of circumstances. In general, however, the larger the watershed, the longer the period of concentration. It is entirely possible, then, that a 10-minute period of concentration may be suitable for consideration with a 10-acre watershed, a 1-hour period with a 100-acre watershed, and a 4-hour period with a 3,000-acre watershed. On the 10-acre watershed the 20 percent increase in slope would increase the peak rate of runoff by but 2 percent to 4 percent for the range of conditions covered by the tables and curves in Part II. For the 100-acre watershed, the increase would be from $2\frac{1}{2}$ percent to 5 percent and for the 3,000-acre watershed, from 3 percent to 7 percent. On the basis of a 100 percent increase in slope, the same analysis would indicate: For the 10-acre watershed, increases of $7\frac{1}{2}$ percent to $14\frac{1}{2}$ percent; for the 100-acre watershed, increases of 12 percent to $23\frac{1}{2}$ percent; for the 3,000-acre watershed, increases of 11 percent to $20\frac{1}{2}$ percent. It should be noted that the higher percentages apply to watersheds having the lowest proportional peak rates of runoff.

The foregoing evaluations indicate that for moderate increases in slope the increases in peak rates are small and often may be neglected. Where the changes in slope are great, some allowances will be necessary. However, it will be found that where the changes in slope are large, such changes are frequently accompanied by changes in soil texture or depth which make extension of original data inadvisable.

It must be recognized that this discussion includes many assumptions and omits considerations which have some bearing, such as refiguring velocities on the basis of new and increased rates of flow corresponding to lessened times of concentrations. Since some of the assumptions cause deviations having opposite effects, it is felt that further refinements would confuse rather than clarify the issue.

Of secondary importance to the effect on velocity of runoff is the effect of slope on depression storage. As slope increases, the amount of water retained in natural depressions decreases until for slopes of 10 percent or more, the amount stored is negligible. On flat slopes and level land, however, small natural depressions may store very considerable amounts of water, especially when supported by conservation practices such as contour cultivation, contour furrows, etc. Since no appreciable runoff can occur until after the requirements of depression storage are satisfied, and a normal characteristic of the intense convectional rainstorms of the High Plains is that maximum intensities occur near the beginning of the storm, depression storage on flat or nearly level land may result in a marked reduction in peak rates of runoff. As pointed out previously, it is seldom good practice to base design of structures on practices which may be changed or discontinued but where there is assurance that practices such as contour cultivation, contour furrows, etc., will be maintained for the life of the structure, this reduction in probable peak rates should be considered if appreciable economies will result.

Drainage Density

Drainage density of a watershed is defined as the length of waterway per acre and is determined by dividing the total length, in feet, of all of the drainageways, both main and tributary, by the area of the watershed in acres. For this purpose, the lengths of the drainageways are measured along the thread of the stream from a point at which a concentration of water sufficient to produce channel flow may be expected under ordinary conditions to the confluence of tributary with principal drainageway, or, for the principal drainageway, generally to the lowest point of the watershed. There may be cases, however, as on Watershed W-II at Colorado Springs, where a principal drainageway debouches into a flat and conditions of overland flow are resumed.

Drainage density serves to indicate the distances which particles of runoff water must travel at the comparatively slow velocity of overland flow. The greater the drainage density, the shorter are the distances separating the drainageways and also the distances over which runoff moves as overland flow. Drainage density is an index of that portion of the time of concentration resulting from overland flow and, with other factors constant, the greater the drainage density, the shorter the time of concentration and the greater the intensity of precipitation which must be considered.

Shape of Watershed

The "form factor," A/L^2, is a dimensionless number serving as an index of the shape of the watershed. It is computed by dividing the area of the watershed in square feet by the square of the length of the watershed, in feet, as measured in a straight line along the general direction of the principal drainageway. Thus, "form factor" is the ratio of the average width of a watershed to its length. A large "form factor" indicates a compact watershed whereas a small "form factor" is characteristic of an elongated watershed.

The shape of a watershed is important in its relation to the time of concentration and, consequently, to the intensity of precipitation which must be considered as producing runoff. As "drainage density" is an index of the average distance which particles of runoff water must travel at the slower velocities of overland flow, so "form factor" is an index of the distance which accumulated amounts of runoff travel at the more rapid velocities of channel flow. In general, the smaller the "form factor," the longer the time of concentration and the smaller the intensity of precipitation which must be considered.

It must be remembered that the factors influencing runoff must be considered in their combined effect. "Form factor" of "drainage density" must not be considered separately. It is quite possible for a watershed to be compact with a large "form factor" and yet have a smooth configuration with a low "drainage density." And, again, common sense must be used in analysis when abnormal conditions are encountered. It is obvious that when a frying-pan shaped watershed is under consideration a higher peak rate may be produced from the pan portion only, neglecting the handle, with its higher "form factor" and only slightly smaller area than from the entire area with its much smaller "form factor."

Soils and Infiltration

Generalities

The soil, its depth, and its conditions have a major influence on runoff, in fact, after the fixed losses of interception and depression storage are satisfied, the amount of water which the soil will receive is the only important factor which reduces the rates of runoff below the intensity of precipitation. However, the rate of infiltration of a soil is not static. It is subject to many influences, some of the more important being vegetal cover, soil texture and structure, subsoil permeability and depth, substratum permeability and depth, composition of soil, diurnal changes and temperature, seasonal changes, effects of intensity of precipitation, soil moisture, cultivation and tillage, surface litter or mulch, and erosion. These influences will be discussed briefly in the following paragraphs, but first, a few generalities about soils and infiltration.

As a general rule, the lighter the soil, the higher the infiltration capacity. Sands, loamy sands, and other light soils will often take water very rapidly for extended periods. Heavy clays, on the contrary, may absorb a little water but quickly become almost impervious with rates of infiltration having a negligible effect on peak rates of runoff. As among the five recognized groups of soil textures, the rate of infiltration increases roughly in geometric progression with a constant multiplier in the order of 3. This

relationship is of little practical value, since the top grade of one group is practically identical with the lowest grade of the next lighter group and the effects of the different influences are not proportionately similar for the different groups.

The normal characteristic of infiltration is to begin at a relatively rapid rate which decreases rapidly during the first few minutes and then more slowly until, usually within an hour, it becomes stabilized or even shows a slight increase. Figure 7, page 34, shows a typical curve indicating the decrease in the rate of infiltration with time and represents results obtained by Sharp and Line (6) on the typical soil of Watershed W-III at Colorado Springs, using a type-F infiltrometer with simulated precipitation.

Rates of infiltration, or infiltration capacity, are limited by two conditions. First, the rate at which water can enter the soil, sometimes referred to as the entrance coefficient and, second, the rate at which water moves down through the soil, sometimes referred to as the transmission coefficient. In many instances, especially where wind erosion is prevalent, the surface conditions are such that the entrance conditions govern. With the heavier soils, the lower permeability results in slow rates of movement, and since water cannot enter the soil more rapidly than it moves down through it, the rate of transmission governs the rate of infiltration.

Vegetal Cover

For a given soil, the density and volume of vegetal cover have a greater effect on rates of infiltration and runoff than any other factor, and, for watersheds having deep soils and pasture cover in the High Plains, probably a greater effect than all other factors combined. Because the effect of vegetal cover includes aspects other than its influence on soil and infiltration and its great importance, consideration of this subject is deferred to the following section.

Soil Texture and Depth

The general effects of soil texture on infiltration have been noted in a preceding paragraph. Textures are based on or correlated with a mechanical analysis of the soils and the proportions of sands, silts, and clays which it contains. This omits consideration of the state of aggregation of the soil. As defined by Baver (1), an aggregate consists of an intimate grouping of a number of primary soil particles into a secondary unit. It is believed that the formation of the smaller aggregates takes place under the influences of micro-organisms, fungi, bacteria, etc., although some may be formed by the cementation of colloidal clay particles. The larger aggregates probably are formed by the action of roots on smaller aggregates. The manner in which the aggregates and the unaggregated particles are arranged constitutes the soil structure. This structure has a profound influence on rates of infiltration and differences in aggregation and structure may result in a moderately heavy soil with good aggregation displaying more favorable infiltration characteristics than a moderately light soil with a minimum of aggregation. Vegetal cover, tillage methods, surface litter, manure, drainage, and irrigation, all have their effects on aggregation for better or worse soil structure. The heavier soils with large proportions of silt and clay particles are, generally, capable of a higher degree of aggregation than lighter soils where sand particles are predominant.

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TYPICAL INFILTRATION CURVE

Bresser Clay Loam Soil

Watershed W-III, – Colorado Springs, Colorado

Infiltrometer determination using simulated rainfall

from Progress Report, Infiltration Studies
by A. L. Sharp and H. E. Line

Figure 7

Rate of Infiltration – Inches per hour

Duration of Precipitation – Minutes
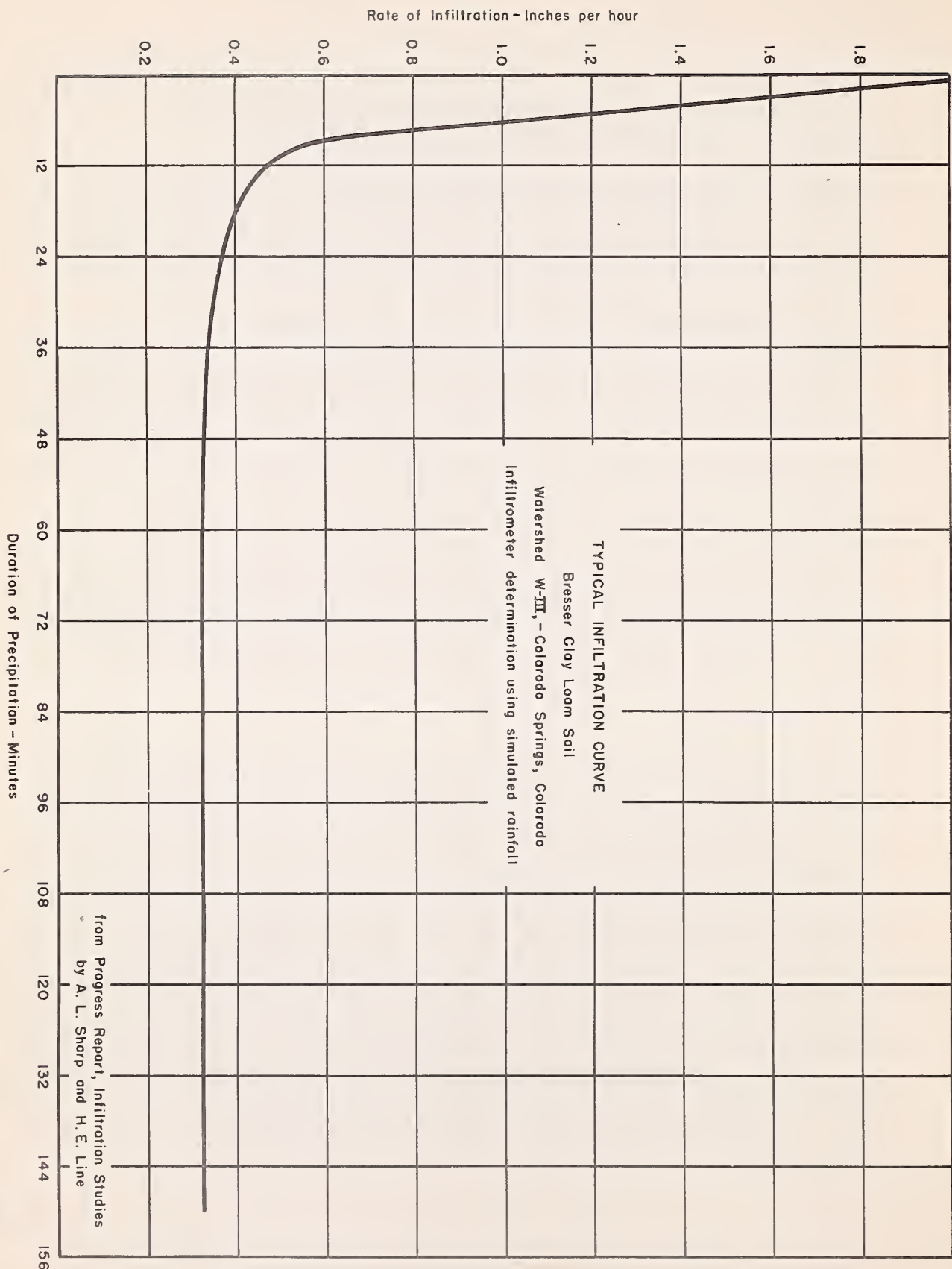
SOIL CONSERVATION SERVICE, WASHINGTON, D.C., 1947

The texture of the soil and its structure also serve as an index of the water-storing capacity of the soil. In the process of infiltration, the water entering the soil first fills the capillary pores. This water is held by capillary action against the force of gravity and does not move down through the soil profile under the influence of gravity, although some movement takes place under capillary attraction. After the requirements of the capillary pores are satisfied, the water moves downward through the larger, non-capillary pores of the soil profile until it meets with an obstruction such as an impeding layer or zone of reduced permeability. The water which continues to enter the soil is then stored in these non-capillary pores until all available space is filled. When this occurs the soil is fully saturated and water can enter the soil only as rapidly as it can penetrate the impeding layer or less permeable zone below. This water stored in the non-capillary pores and subject to movement under the force of gravity is known as gravitational water.

The capacity of the soil to store water is highly variable, depending on the proportions of the sizes and the arrangement and composition of its constituent mineral particles and the amounts of organic matter contained. According to Meyer (5), capillary water (including hygroscopic water) may range from about 0.3 inch of water per foot depth of soil for sands to about 4-1/4 inches for clays. Gravitational water in saturated soils may be as much as 4.4 inches per foot depth of soil for sands or as little as 0.8 inch for clays. Every soil will have its own characteristic capacity for water-holding or water storage. For the soils under consideration in the High Plains of Colorado and New Mexico, the storage capacity for gravitational water will be of the order of 3 to $3\frac{1}{2}$ inches per foot depth of soil for moderately light soils, ranging downward to $1\frac{1}{2}$ to 2 inches for moderately heavy soils. The holding capacity for capillary water, above the wilting point, will be of the order of 0.5 to 0.8 inch per foot depth of soil for moderately light soils, ranging upward to 1.2 to 1.5 inches for moderately heavy soils.

Permeability and Depth of Subsoil

Subsoil permeability has an influence on rates of runoff inversely related to the depth of the topsoil. As has been pointed out, the process of infiltration involves the rate at which water enters the soil and the rate at which it is transmitted through the soil. When the permeability of the subsoil is such that it will not transmit water as rapidly as the topsoil above, the difference in rates must be stored in the pores of the topsoil. Only when the topsoil becomes fully saturated will the rate of infiltration of the profile be affected by the lower permeability of the subsoil. Of course, if the subsoil is more permeable than the topsoil, the greater permeability can have no effect on the rate of infiltration. If the topsoil is deep, the type of rainfall expected in the High Plains (a maximum of 3.50 to 4.25 inches in 24 hours for a 25-year expectancy or 3.0 to 3.5 inches for a 10-year expectancy according to Yarnell (8)) will seldom saturate the topsoil so completely as to affect the rate of infiltration. If the mantle of topsoil is shallow, as in some of the soils of eastern New Mexico, with thin, moderately heavy topsoils underlain by slowly permeable subsoils, the effect of the lower rate of transmission of the subsoil will govern surface infiltration under long-continued rainfall.

Permeability and Depth of Substratum

Of the soils being considered in the High Plains of Colorado and New Mexico, none show a condition where the permeability of the substratum is less than that of the subsoil. Should such a condition be found, the effect on the rate of infiltration will be the same as discussed in the preceding paragraph. Only when the topsoil and the subsoil are both saturated will the lower permeability of the substratum govern the rate of infiltration. This will be a rare occurrence and is most apt to be found where severe erosion has occurred.

Composition of Soil

The composition of the soil has a pronounced effect on the rate of infiltration. Certain clay particles, when in contact with water, swell considerably. The amount of the swelling seems to depend upon the size and shape of the colloidal particles and these, in turn, are related to the chemical composition. The swelling of the clay particles closes the spaces available for the passage of water, decreasing the permeability and the coefficient of transmission. For example, the sealing properties of the bentonite clays are well known and utilized for practical purposes such as sealing of irrigation canals, etc. Laboratory reports of the Bureau of Reclamation (3) list numerous bentonite samples showing swell exceeding 500 percent and bentonite-soil mixtures with permeabilities less than 1 inch per year.

Diurnal Changes and Temperature Effects

The diurnal variation of the rate of infiltration is probably an effect of temperature and is principally, though not entirely, related to the viscosity of water. Sharp and Line (6) found in experiments with tubes and sprinkled plots that the rate of infiltration varied with the temperature. The experiments were made at different seasons of the year and were continued for periods of more than 72 hours. On sprinkled plot tests, a change in temperature of 27° F. from low to high on three consecutive days was accompanied by increases in the rate of infiltration averaging 0.20 inch per hour, or about 70 percent change above the average of the rates prevailing at the low temperatures. This effect indicates that, with all other conditions equal, higher rates of runoff should be expected from a storm occurring during the coolest part of the night than from one occurring during the heat of the day. In general, the most intense storms occur during the afternoon when preceding temperatures have been high, but high intensity storms during the night or early morning are not infrequent. The highest intensities of precipitation recorded at the runoff studies projects in the High Plains, occurred at 6:00 a. m. when the temperatures of air and soil were at their lowest.

Seasonal Changes

Sharp and Line (6), as a result of experiments in 1940 and 1941, conclude that there is a seasonal trend in rates of infiltration. Their experiments indicate that, for the location and soils investigated, the maximum rates of infiltration occur in the spring months of April and May, declining rapidly from the middle of May through June, and continue to decline moderately until October. From November to May rates of infiltration improve gradually. The experiment included too brief a period to be conclusive but serves to confirm theories held previously. These theories hold that the action of

frost in the cold season restores infiltration capacity and that the transportation of "fines" carried in suspension by runoff water into soil pores by the earliest excessive rainstorms starts the decline in rate of infiltration.

This seasonal trend, if confirmed, will indicate the occurrence of diminished rates of infiltration and resulting increased rates of runoff at the time of the most frequent occurrences of high intensities of precipitation.

Effects of Intensity of Precipitation

The intensity of precipitation influences rates of infiltration principally through its mechanical action. The more intense the precipitation, the greater the impact of raindrops striking the soil. This impact of raindrops tends to break down the soil aggregates to smaller aggregates and to primary particles of sand, silt, and clay. It also tends to stir up the finer soil particles and to transport them in suspension while slightly larger particles are rolled along on the surface. This creates a muddy or turbid condition. As the turbid water moves in overland flow, a portion enters the pores of the soil carrying with it the fine soil particles in suspension. These particles are quickly filtered out and deposited in the pore space reducing the infiltration capacity. Under very intense precipitation, this process may alter the characteristic infiltration curve, causing an even more rapid decrease in rate and eventual stabilization at a lower level. A portion of this effect will remain throughout the season, but after drying out, generally a portion of the lost infiltration capacity is recovered.

Another effect of increased intensity of precipitation is particularly noticeable on grassed lands. Sharp and Line (6) found that the rate on infiltration under natural precipitation was, for the soil investigated, about one-half of that determined using the simulated rainfall of the infiltrometer. For various runoff producing rains, the observed rates of infiltration were from 20 percent to 70 percent of the rates determined by the infiltrometer under similar conditions. This difference is believed due to the uniformly high rates of the simulated rainfall which resulted in all portions of the plots being completely covered by the surface detention. With the bunch grass vegetation typical of the High Plains, this greater depth of surface detention covered the soil near the plants as well as some of the crowns. The soil near the crowns of the plants is somewhat more permeable than that between bunches due to greater biological activity, more organic matter, and spaces left by decaying roots. For this reason, the greater depth of surface detention occasioned by more intense precipitation results in a greater area of surface and a more permeable soil being exposed to the infiltration process.

Soil Moisture

The effect of soil moisture on rates of infiltration and runoff is obscure. Baver (1) cites a number of observers who report that rates of runoff are greater and rates of infiltration capacity are less when soil moisture is high. Sharp and Line (6), reporting on sprinkled plots, found no significant differences in rates of infiltration as between moderately dry soils and soils at or near field capacity of moisture.

Based on the 9-year period of observation of runoff studies at Colorado Springs, it appears that the effect of soil moisture on rates of infiltration and runoff varies with different soils and that no generalization is advisable. On Watershed W-IV at Colorado Springs, it appeared that the drier the soil, the less pervious it became and the higher

the rate of runoff recorded. On Watershed W-I, as the soil moisture increased, the rates of runoff recorded also increased. The following examples illustrate the different trends.

On Watershed W-IV, on August 10, 1938, a rain having an average intensity of 3.96 inches per hour during a 14-minute period of rise produced runoff at a peak rate of 2.33 inches per hour. At this time the surface of the soil, where exposed, was hard and dry. Only 0.03 inch precipitation had fallen during the preceding 15 days. Average soil moisture in the top 6 inches of soil was less than 2 percent and for the soil-depth zone 6 inches to 24 inches, was but 3-1/4 percent. On August 2, 1939, a rain of almost identical average intensity, 3.92 inches per hour, through a 17-minute period of rise produced a peak rate of but 1.49 inches per hour, or 36 percent less than the rain of the previous year. At this time there was an appreciable amount of moisture in the soil, though not approaching field capacity. Precipitation had amounted to 0.48 inch during the preceding 15 days. Average soil moisture in the top 6 inches of soil was $5\frac{1}{2}$ percent and in the soil zone, 6 inches to 24 inches, was $4\frac{1}{2}$ percent. Average field capacity of the soil is approximately 14 percent for the top 6-inch zone and 11 percent for the 6-inch to 24-inch soil zone. The soil is described as "medium depth, moderately sandy loam developed from re-worked arkosic materials with 20 percent to 25 percent angular feldspathic and quartzitic gravel, 2 mm. to 1 cm. in diameter."

On Watershed W-I, on July 10, 1945, the soil was fairly dry. Only 0.23 inch of rain had fallen in the 15-day period preceding. One of the heaviest rains ever recorded on this watershed fell during the early evening. During the first 20 minutes of the storm, no runoff occurred although 0.49 inch of rain fell during this time, which included a 9-minute period with an average intensity of 2.10 inches per hour. After the runoff started, the maximum rate of runoff of 1.94 inches per hour occurred after 20 minutes. For this storm, rainfall minus runoff was 1.35 inches, most of which was absorbed by the soil.

Fifteen hours after cessation of this rain another rain of high intensity was recorded. Runoff was recorded simultaneously with the beginning of precipitation and the all-time peak of runoff, 3.31 inches per hour, occurred after 9 minutes. The average intensity of precipitation for the 9-minute period was 2.73 inches per hour. For this storm, rainfall minus runoff was 0.16 inch.

A third intense storm followed the second in 25 hours. Runoff was recorded 2 minutes after the beginning of rainfall and the peak of runoff, 2.88 inches per hour, was reached in 9 minutes. The average intensity of precipitation for the 9-minute period was 2.40 inches per hour.

The effect of soil moisture in this instance is illustrated in that a 9-minute average intensity of precipitation of 2.10 inches per hour on dry soil produced no runoff. Two days later after approximately 1.50 inches had been added to the total soil moisture, a storm with an intensity for the same period only slightly greater, 2.40 inches per hour, produced runoff with one of the highest peak rates recorded on this watershed. Watershed W-I is cultivated and has a topsoil described as a "moderately heavy, friable brown clay loam with crumb structure." This watershed has been subject to severe to very severe wind erosion.

Cultivation and Tillage

Cultivation of the soils of the High Plains of Colorado and New Mexico generally results in lowered rates of infiltration and increased peak rates of runoff. The development of a plow sole is usually accompanied by a sharp decrease in permeability at that depth which has the same effect as a less permeable subsoil which was discussed earlier in this section. Continued cultivation usually results in a depletion of the organic matter in the soil and by mechanical action breaks down the larger aggregates. The aggregates in the heavier soils are more easily destroyed by tillage operations, and permeability decreases more rapidly than in lighter soils. Many crops leave large percentages of the surface bare and unprotected from the impact of high intensity rain and exposed to the action of wind. Water erosion removes portions of the topsoil much more readily than when the soil has a native-pasture cover. Under most types of cultivation there is a marked decrease in biological activity in soil building. Baver (1) points out "that the soil fauna are most abundant where there is ample vegetative cover. This is particularly true of dense sods and good forest covers." The result of these various actions over a period of time frequently results in the lowering of the soil permeability by one classification group. Cultivated Watershed W-I at Colorado Springs is in a field completely surrounded by fields having virgin native-pasture cover. The soils of all are similar and there is every indication that the original soil condition of this watershed was the same as its surroundings. Recent surveys of the surrounding fields with native-grass cover class them as having a medium-textured topsoil whereas the topsoil of Watershed W-I is rated as having a moderately heavy texture. This is due primarily to the removal by erosion of a portion of the original topsoil and an intermingling of portions of the subsoil by the mechanical processes of cultivation. Methods of tillage and crop management which have been discovered or rediscovered during recent years, such as subsurface cultivation, chiseling of the subsoil, management of residues, etc., and practices such as contour cultivation, terracing, strip cropping, and rotations all assist in retaining the higher infiltration capacity which existed under the original virgin sod or forest cover. It is doubtful, however, that under any system of cultivation of row crops the original infiltration capacity could be maintained.

Surface Litter or Mulch

The effect of surface litter or mulch on cultivated fields has been reported by Duley and Russel (2) as very effective in maintaining or even increasing the infiltration capacity, especially when combined with methods of cultivation which leave these residues on the surface. In one test, sprinkled plots with wheat stubble and combine residues showed runoff only about 5 percent as great as from bare cultivated land. Field plots under natural precipitation showed similar results. With surface litter and subsurface tillage, runoff was only 40 percent to 50 percent as great as on fields without litter and cultivated by conventional methods.

Erosion

The effects of erosion and the accompanying deposition tend to decrease infiltration capacity and increase rates of runoff. Sheet and wind erosion in removing the topsoil remove much of the organic matter of the profile and render it less hospitable to the organisms which build up soil aggregates and maintain soil structure. Complete removal of the topsoil exposes subsoils which are usually less permeable and which cannot support as dense vegetation as formerly existed. With less dense vegetation, the

effect of impact of raindrops is greater and runoff takes place at higher velocities, and more rapid concentration of runoff takes place.

Wherever wind erosion takes place, it is accompanied by deposition, possibly in the same field, or in an adjacent field, or, perhaps, many miles away. The result of this deposition is to reduce infiltration capacity and increase peak rates of runoff. The action is twofold. First, the deposits of wind-borne soil are usually made up of the finer unaggregated soil particles. Under runoff-producing rains, these particles are readily transported in suspension and enter the soil pores where they are filtered out and left in the pores of the soil. This reduces the size of the pores and their capacity to convey water and thereby reduces the transmission coefficient of infiltration. The second action is that of forming a slowly permeable film over the surface which effectively limits infiltration by reducing the entrance coefficient. The author has observed this action in eastern Colorado during the period of the dust storms in 1934 and 1936. The first drops to fall on these dust deposits would each spread out forming a "slick" spot about 2 inches in diameter. In a very brief time the surface would be covered with an almost impermeable layer and practically no infiltration could take place. Several showers of one-half inch of rain, or more, were observed where so little moisture penetrated the surface that dusty conditions would exist in these fields within 2 or 3 hours after cessation of rainfall. Fortunately, these conditions are not lasting, since, in most cases, the wind-deposited material becomes an integral part of the soil sooner or later under the action of rain, snow, vegetation, and micro-organisms. It is, however, a condition which may come into existence whenever conditions become right and is, for the land-owner at a distance from the seat of erosion, one that he can do little to prevent.

Gully erosion also tends to increase peak rates of runoff. Moving down through a broad swale, runoff moves at moderate velocities in a wide shallow stream retarded by good growths of vegetation. When the swale is cut by a gully, the velocity increases, since flow is in a much narrower channel with a correspondingly greater hydraulic radius and the retarding influence of vegetation is lacking. This increased velocity results in a shorter time of concentration and the necessity of considering higher intensities of precipitation.

Gullies have an additional effect in reducing the time of concentration as they cut back into areas where overland-flow conditions formerly existed. In this way, drainage density of a watershed is increased with results as discussed in an earlier section.

Influences of Vegetation

In the High Plains of Colorado and New Mexico where effective soil material above an impeding layer is deep and occurrence of precipitation in amounts sufficient to saturate this deep soil profile is rare, the influence of vegetation on runoff is probably greater than that of all other influences combined. Observations cited in following paragraphs indicate that the peak rate of runoff from a watershed with poor vegetal cover may be 25 to 40 times as great as runoff from the same watershed when vegetation is good.

Vegetation influences runoff directly and indirectly. The direct influences are principally the mechanical effects incident to interception and retardance of flow. The indirect influences are principally the soil changes which are encouraged by the presence of organic matter and the processes of decay.

In the previous section when considering the effect of intensity of precipitation on soils and infiltration, it was pointed out that one of the effects was in disrupting aggregates and another in creating turbidity of the surface water. The action of a canopy of vegetation is to intercept the raindrops at some distance above the soil and absorb the impact in whole or in part. Under a canopy of vegetation, raindrops are converted into a spray which settles to the surface of the soil as droplets without sufficient energy to break up aggregates or to stir up particles of soil. Other drops accumulate and slide down stems or drop short distances with little impact. The resulting flow over the surface is clear and free from turbidity. It enters the soil freely and without carrying with it particles to be filtered out and clog the soil pores. This effect is even more pronounced when a litter of dead grass covers the bare soil between plants. For this action, the volume of vegetation is quite important and the basal density has little influence. A stand of Russian thistle with a thick mass of foliage but with a very low basal density will break up the raindrops almost as effectively as a dense stand of vegetation having no greater volume of foliage. The other mechanical effect is the obstruction offered to flow by the stems and lower leaves of the plants. Where the vegetation close to the ground is thick, the retardance of the flow as it winds through and around the vegetation is considerable, the velocity of flow is very materially reduced and the depth of surface detention is increased. For this action, the basal density is more important than the volume of vegetation.

It should be pointed out that many surveys of vegetal cover list the condition as excellent, good, fair, or poor depending upon the composition and its palatability for grazing purposes. The influence of vegetation on runoff has nothing to do with the quality of vegetation for beef production but depends upon its effectiveness in intercepting raindrops and retarding runoff and upon its influences in building up soil structure.

The indirect effects of vegetation are in the effects which it has upon soil structure, and on the infiltration capacity of the soil. It has been pointed out previously that the population of soil-building organisms under a good sod is far greater than where the soil is bare. The vegetation furnishes the organic matter upon which the bacteria, fungi, worms, and other organisms feed. The presence of the organic matter in the soil increases the permeability. The organic litter on the surface acts as a filter in addition to affording hospitality for micro-organisms. The root system serves to bind the smaller aggregates into larger aggregates, and decaying roots leave channels affording a ready ingress for moisture.

The influence of vegetation on soil structure is believed to account, at least in part for the higher rates of runoff to be expected from the moderately light soils typified by Watershed W-II at Colorado Springs as compared with the medium-textured soils of the nearby Watershed W-III. Identical methods of analysis of the data obtained over an 8-year period of record indicate that peak rates of runoff with expectancies of 25 years for conditions of which Watershed W-III is representative will be but approximately two-thirds as great as those for conditions of which Watershed W-II is typical. As pointed out in the discussion of the influence of soil textures, soils with the larger sand particles predominating are not as subject to aggregation and improvement in soil structure as are soils with silt and clay particles. In addition, the normal organic-matter content

of the lighter soils is less than that of heavier soils.[5] Over the 8-year period there had been a moderate improvement in density and volume of vegetation on Watershed W-II but the improvement did not compare with that on Watershed W-III. It seems that with the improvement in vegetation on Watershed W-III there has been a corresponding improvement in aggregation and soil structure and a resultant improvement in infiltration capacity. A portion of this improvement was measured by Sharp and Line (6) but their measurements include only 2 years, whereas the improvement in vegetation has continued for four additional years. Examples of the increase in rates of runoff under poor conditions of cover as compared with good conditions follow: At Vega, Tex., the vegetal cover on Watersheds W-I and W-II was poor in 1938 when runoff studies began observations. Not only had the five previous years been very dry with annual precipitation ranging from 16 to 32 percent below normal but these were years of dust storms and of economic stress when overgrazing was the general practice. The combined influence of drought, dust, and overgrazing had resulted in a deteriorated condition of vegetal cover that probably approached the optimum for the production of peak rates of runoff from grassed lands. The growth of winter wheat on the cultivated portions of Watershed W-I was so slight that the field was not harvested. On May 30, 1938, the second most intense rainstorm of the 6-year period of record resulted in the maximum rates of runoff for the entire period. The maximum rate from Watershed W-I was 110 cubic feet per second and for W-II was 141 cubic feet per second. The following years saw relief from overgrazing and diminution in the number and severity of dust storms. Successive wet years in 1941 and 1942 resulted in great improvement in both density and volume of vegetation. This continued in 1943. Basal density counts at the close of 1942 indicated a general improvement of from 50 percent to 100 percent since the inception of the work in 1938. No measurements were made of the volume, but visual inspection revealed an enormous increase as well as a normal accumulation of litter on the surface.

On May 27, 1943, a rainstorm with precipitation 14 percent to 25 percent more intense than the 1938 storm occurred on Watershed W-I and resulted in a peak rate of runoff of but $2\frac{1}{2}$ cubic feet per second. This compares with a peak rate of 110 cubic feet per second 5 years earlier. On August 10, 1942, the most intense rainstorm for the period of record with intensities 14 percent to 25 percent greater than the 1938 storm produced runoff on Watershed W-II at a rate of less than 4 cubic feet per second. This compares with a peak rate of 141 cubic feet per second for the earlier storm.

These records of storms with intensities about 15 percent smaller producing runoff at rates 30 to 40 times as great are startling. Yet, there had been no change in topography, the soil-moisture condition was fairly comparable as evidenced by the comparable rainfall during the 15-day periods preceding the storms. The only noticeable changes in the watershed during the intervening years were in the density and volume of the vegetation and in the litter on the ground surface.

An even closer parallel occurred on Watershed W-III at Colorado Springs. Two of the most intense storms recorded on this watershed occurred on July 21, 1940, and July 15, 1944. The storms were very similar in intensities through critical periods and

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[5]It is recognized that it is possible to build up the organic-matter content of light soils to as high a point as that of heavier soils, but light soils lose their organic matter more rapidly and equivalent organic-matter content can be maintained only by frequent additions of organic materials.

in total rainfall. They occurred at the same season of the year and at about the same hour of the day. The precipitation for the 15-day period preceding as well as for the 6 months previous was reasonably alike. The watershed boundary is defined by an artificial ridge which precludes entrance of water from outside or loss of water to the outside. There had been no appreciable disturbance of the soil nor of the topographic features. With the exception of vegetal cover, all conditions were as similar as is apt to be found under natural conditions. The changes in vegetation were pronounced. In 1938, migratory grasshoppers had cut back vegetation almost to the roots. The total rainfall in 1939 was but 5.24 inches and native grasshoppers gave severe treatment to such vegetation as did develop. As a consequence, many plants did not survive the winter and in the spring of 1940 the density of vegetation was sparse, and with low June precipitation, volume of vegetation was greatly subnormal. In marked contrast, in 1944 the density of vegetation had made a good recovery and the volume of growth was good. Under these conditions, a storm in 1940 which averaged 5 percent less intense than the storm of 1944 produced runoff at a rate 27 times as great. Sharp and Line (6) in their investigations of infiltration characteristics on Watershed W-III established 10 permanent plots scattered uniformly over the watershed. These plots were equipped with tanks and recording instruments measuring precipitation and rates and amounts of runoff under conditions of natural precipitation. Nine of the ten plots were established on the slopes while one plot was located in the drainageway. The drainageway occupies about 10 percent of the area of the watershed. Its soil is a moderately heavy Nunn clay loam and supports a good growth of Bouteloua gracilis (Blue grama) and Agropyron smithii (western wheat grass) with a basal density ranging from 16 percent to 50 percent. The slopes occupy 90 percent of the area with a soil classified as a medium-textured Bresser clay loam to sandy clay loam. Vegetation is almost entirely Bouteloua gracilis (Blue grama) with an average basal density of about 8 percent. Under several moderate rains runoff was recorded on the 9 plots on the slopes but none from the plot in the drainageway nor any from the watershed as a whole. Apparently the dense vegetation on 10 percent of the area had created a soil structure with an infiltration capacity which, in spite of its heavier texture, was able to absorb not only the precipitation falling directly on it but also the runoff from an area 9 times as large. Infiltrometer records indicated that the soil of the drainageways, though heavier, had an average infiltration capacity 2.3 times as great as that of the soil of the slopes.

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